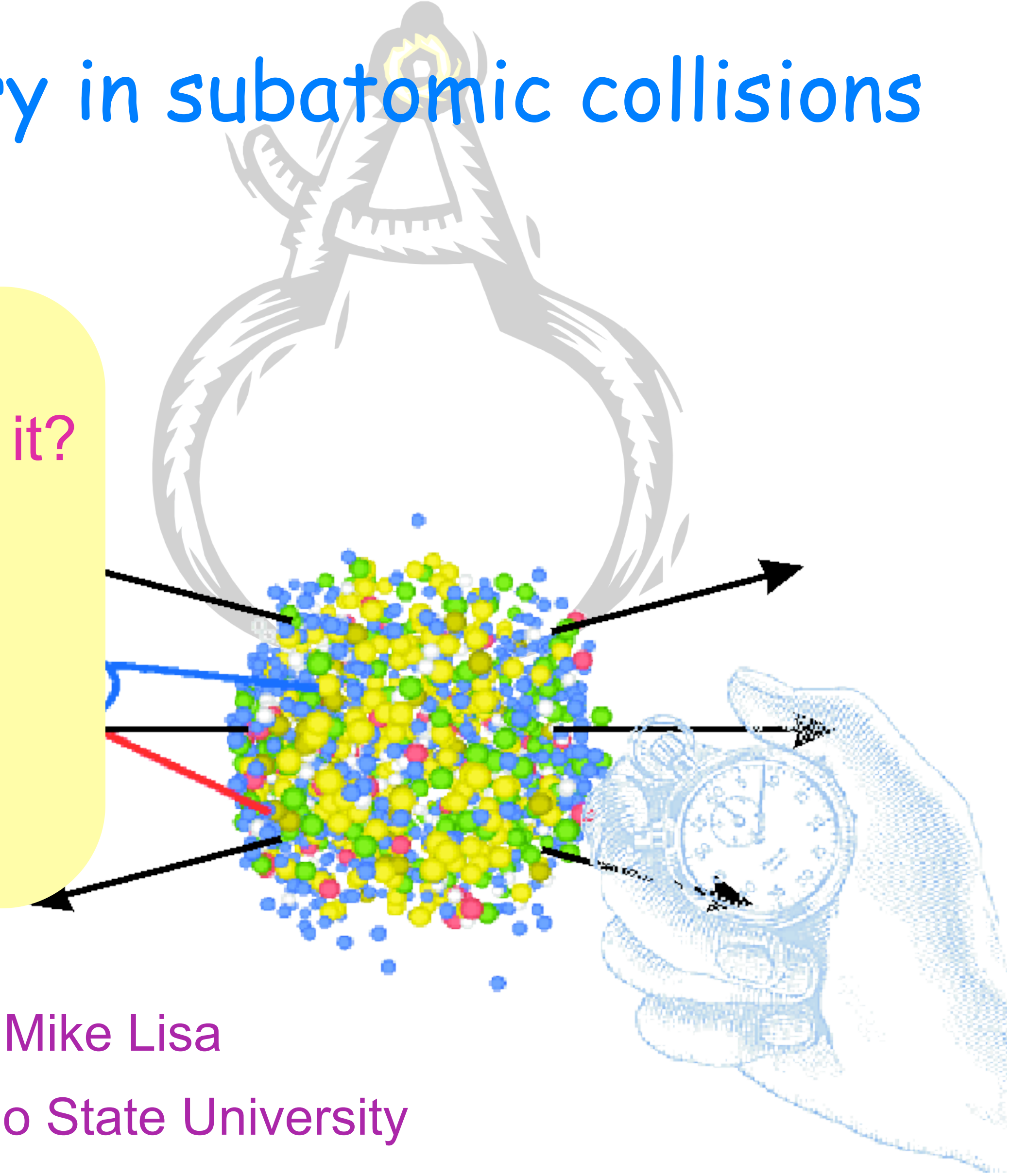
Size Matters

Spacetime geometry in subatomic collisions

- What is the strong force? Why must we understand it?
- How can we study it?
- What tools do we use?
- Why size matters, & what it's told us



Mike Lisa

The Ohio State University

Disclaimer

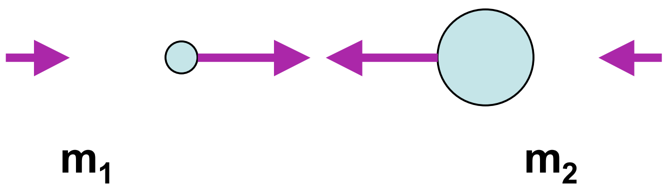
many of the concepts I will present are
"works in very active progress"

an unavoidable consequence of exciting, cutting edge science

Forces and structures in Nature

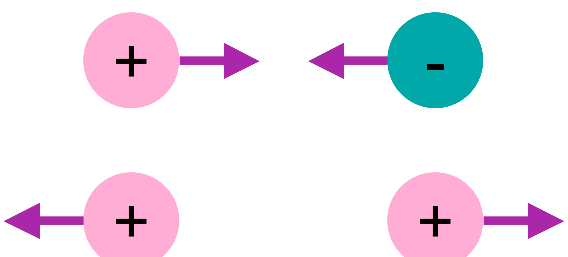
1) Gravity

- one “charge” (mass)
- force decreases with distance

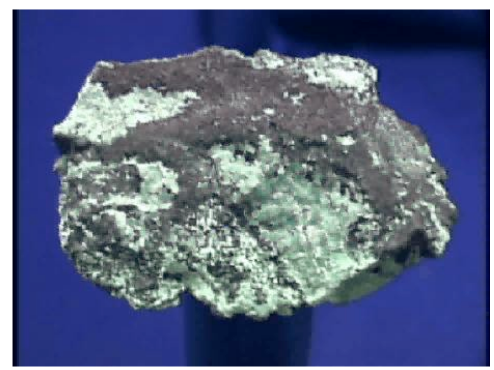


2) Electric (& Magnetic)

- two “charges” (+/-)
- force decreases with distance



Atom



Atomic nuclei and the "nuclear" force

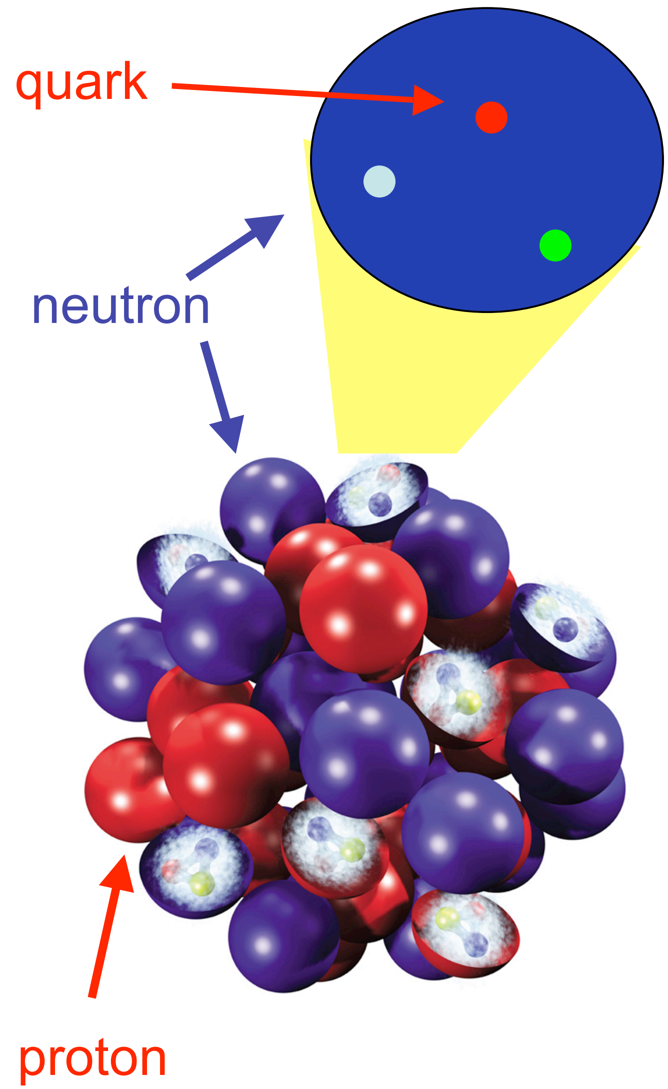
Nuclei composed of:

- protons (+ electric charge)
- neutrons (no electric charge)

Does not blow up!? → "nuclear force"

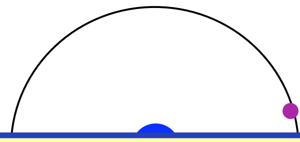
- overcomes electrical repulsion
- determines nuclear reactions
  (stellar burning, bombs…)

- arises from fundamental strong force (#3)
  - acts on color charge of **quarks**



An analogy… and a difference!

to study structure of an atom…

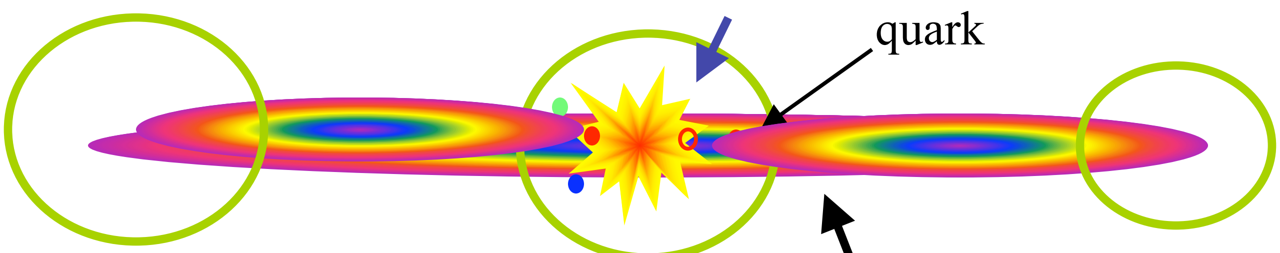


…separate constituents

To understand the strong force and the phenomenon of confinement:
Create and study a system of deconfined colored quarks (and gluons)

Confinement: fundamental & crucial (but *not* understood!) feature of strong force
- colored objects (quarks) have ∞ energy in normal vacuum

•

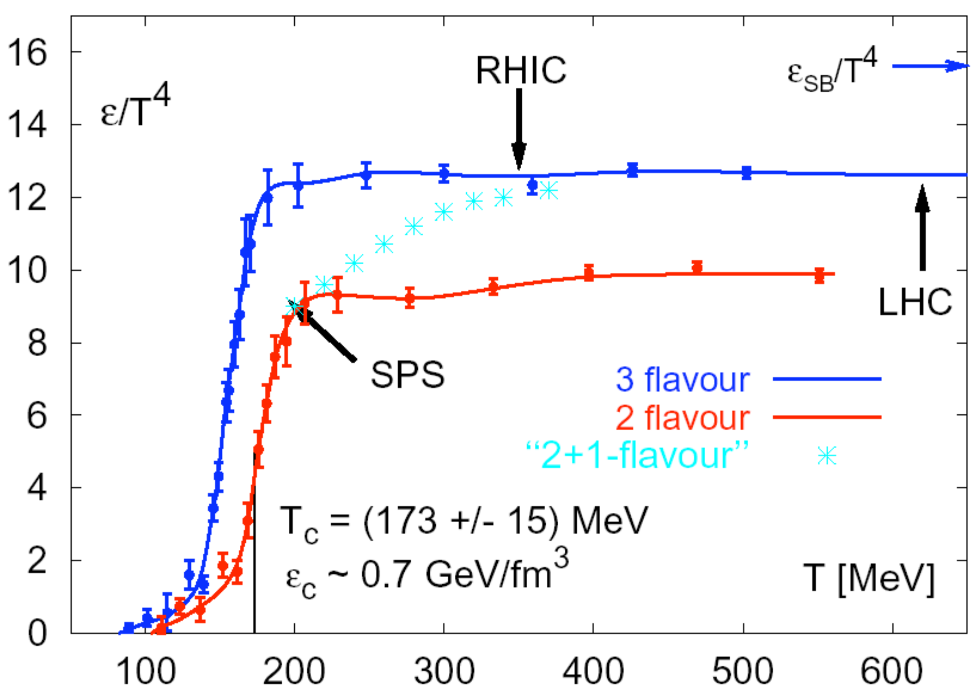


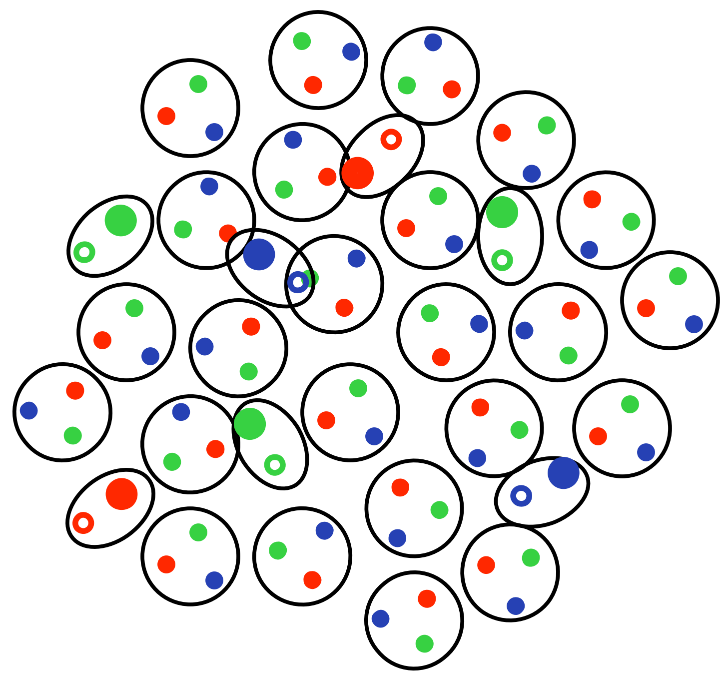
Generating a deconfined state

Present understanding of
Quantum Chromodynamics (QCD)

- heating
- compression

→ *deconfined color matter !*



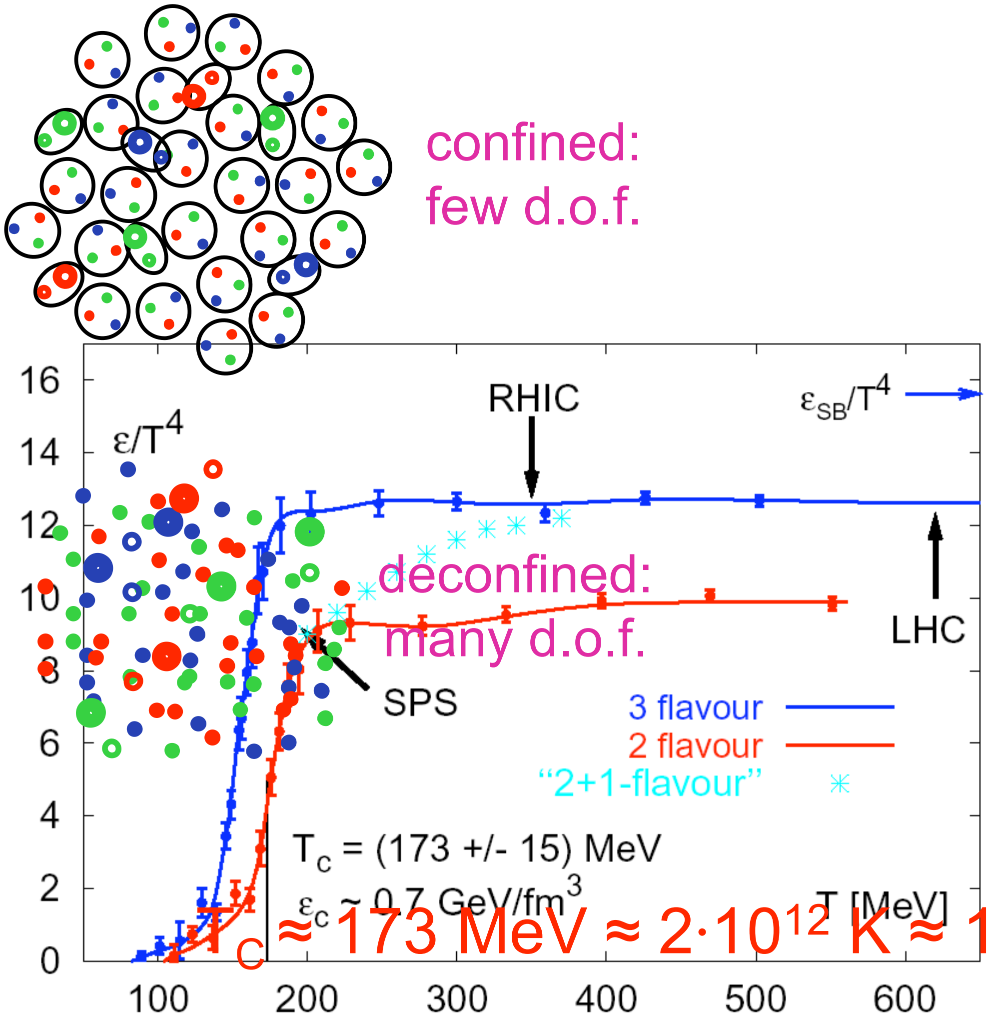


Quark Gluon Plasma
Hadronic Matter
Nuclear Matter
deconfined!
(confined)

Expectations from Lattice QCD

ε/T^4 ~ # degrees of freedom

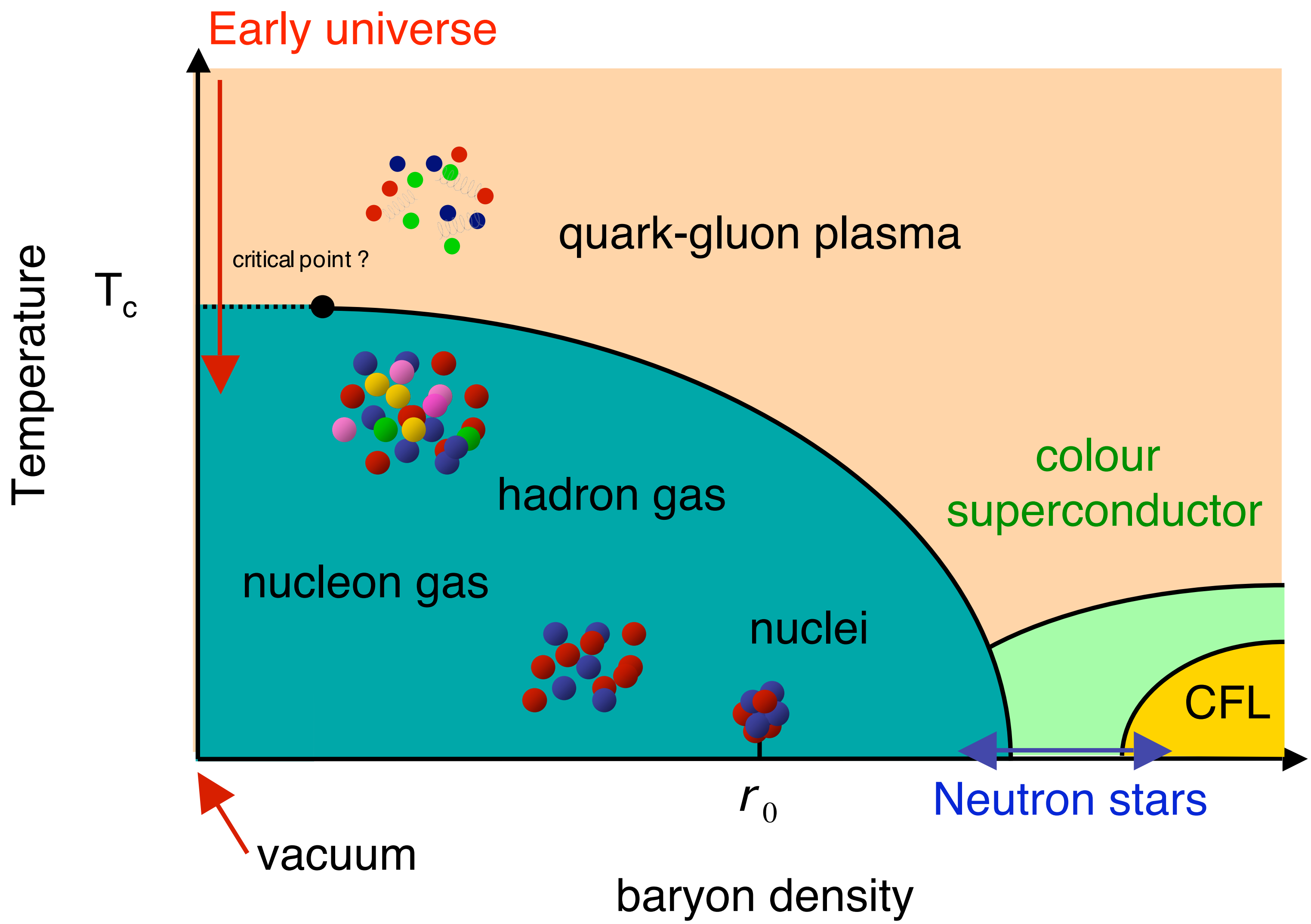
confined:
few d.o.f.



deconfined:
many d.o.f.

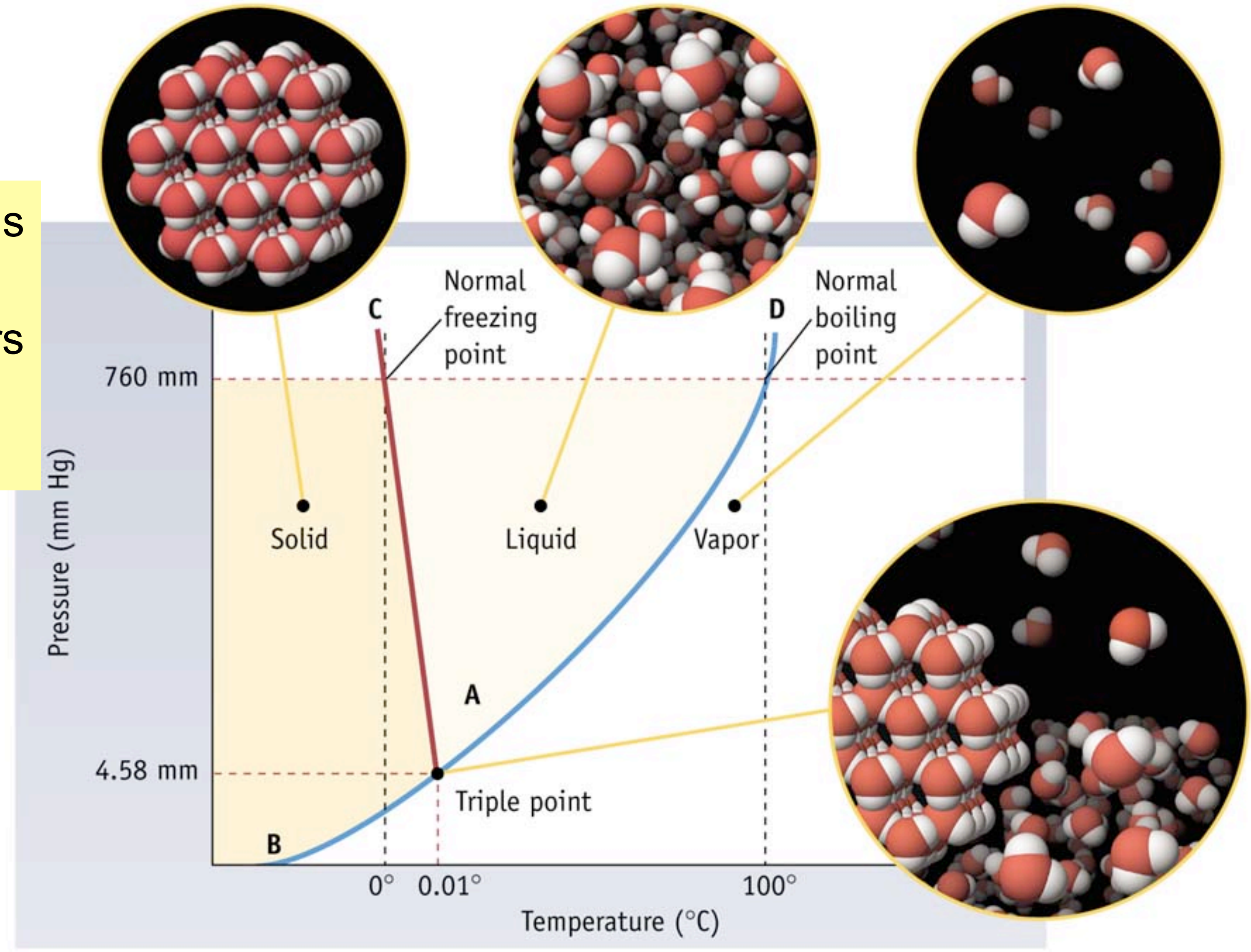
$T_C \approx$ 173 MeV $\approx 2\cdot10^{12}$ K $\approx$ 130,000·T[Sun's core]

The phase diagram of QCD



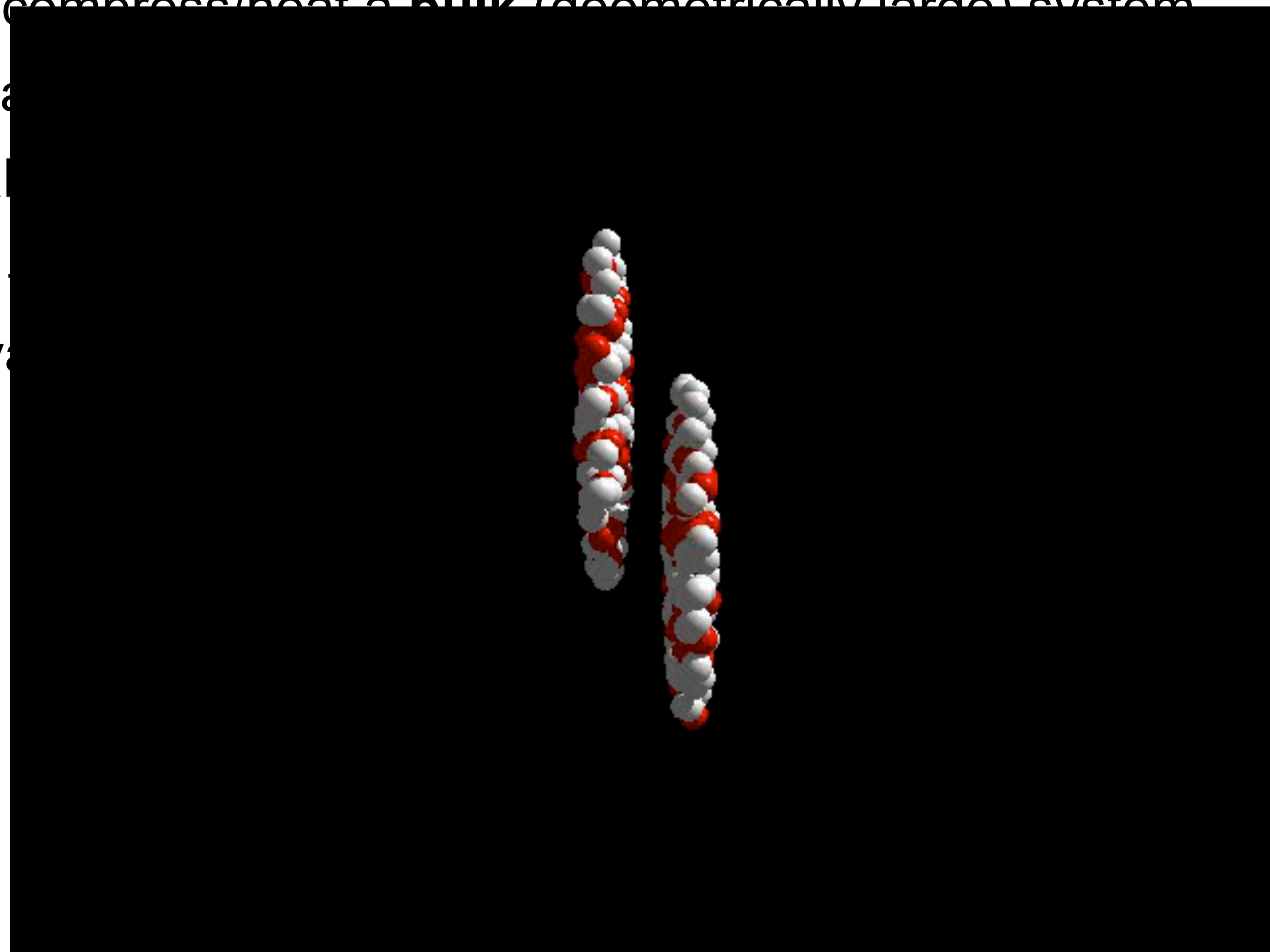
The phase diagram of water

Analogous graphs
- superfluids
- superconductors
- metal/insulator
- …

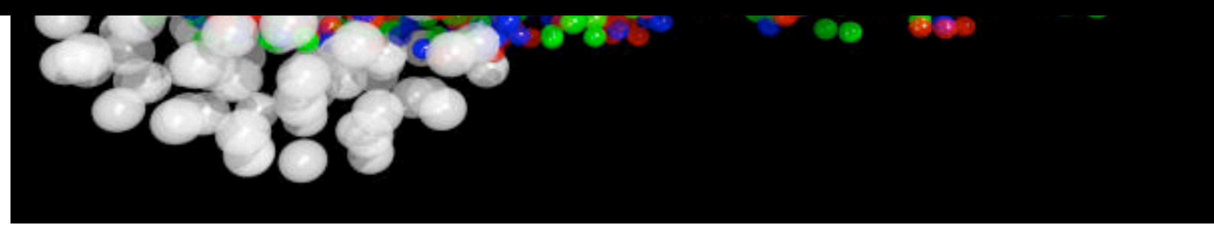


Bulk Matter

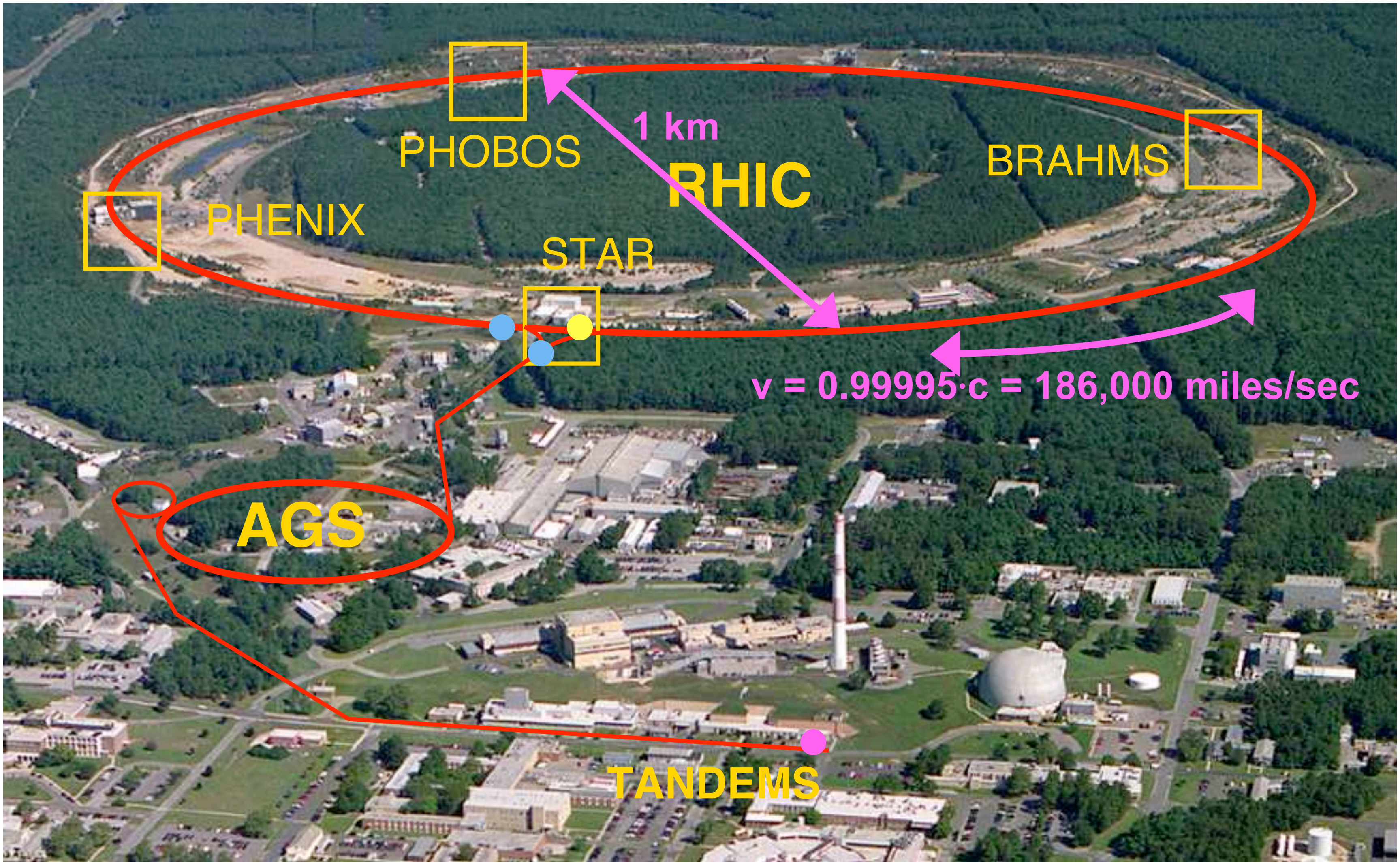
- We must create/compress/heat a **bulk** (geometrically large) system
  - freeze/melt a
  - fundamental
- *Only* achievable t
  at the highest ava C)



1000's of
particles produced
in *each* collision



Relativistic Heavy Ion Collider (RHIC)



Relativistic Heavy Ion Collider (RHIC)

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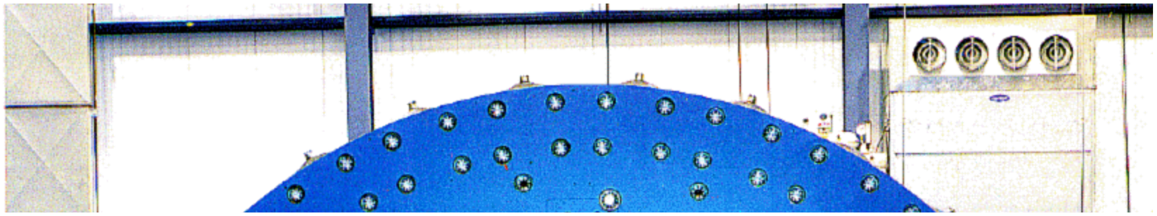
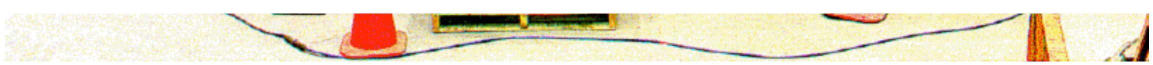
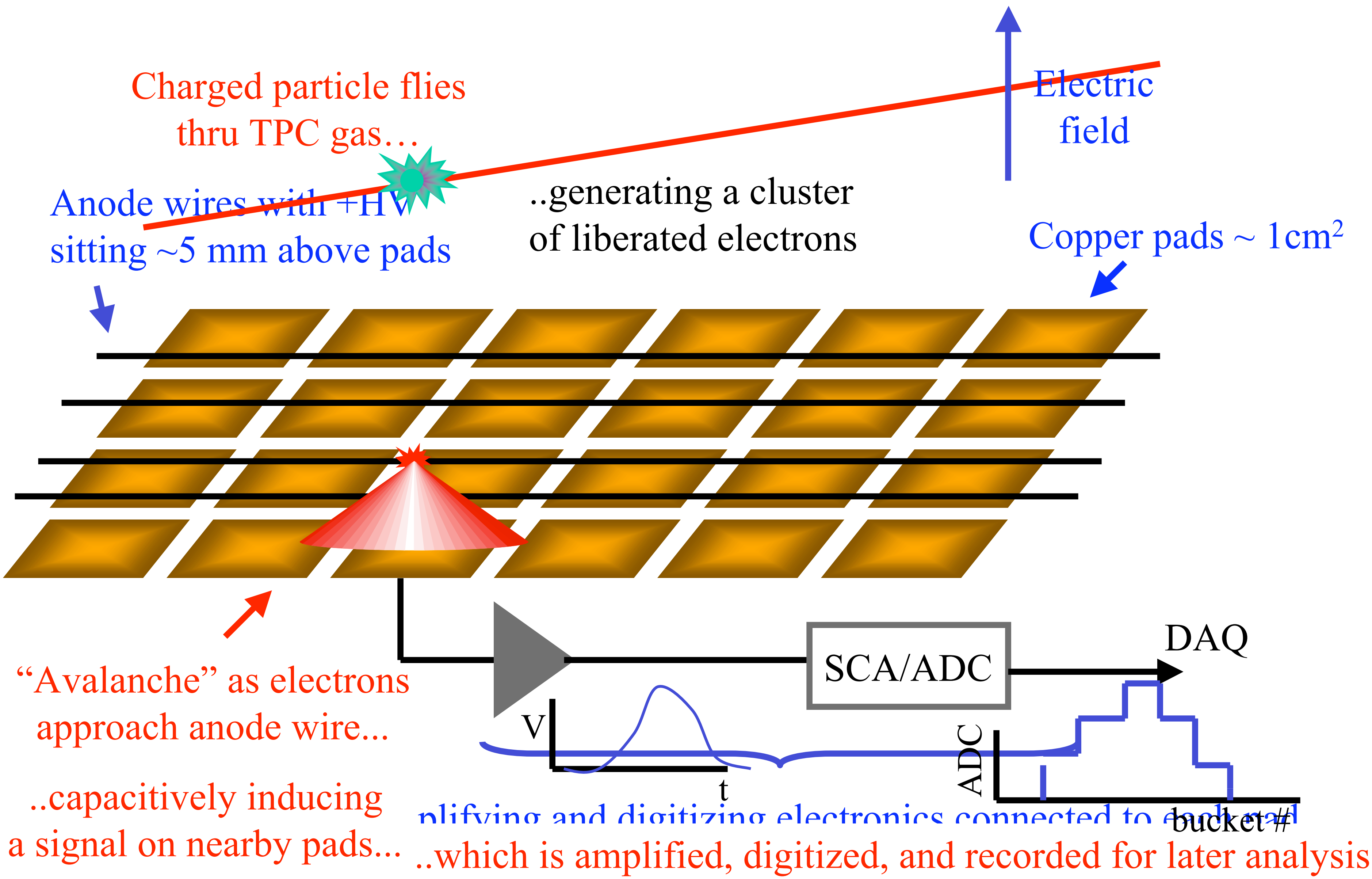


Solenoidal Tracker At RHIC

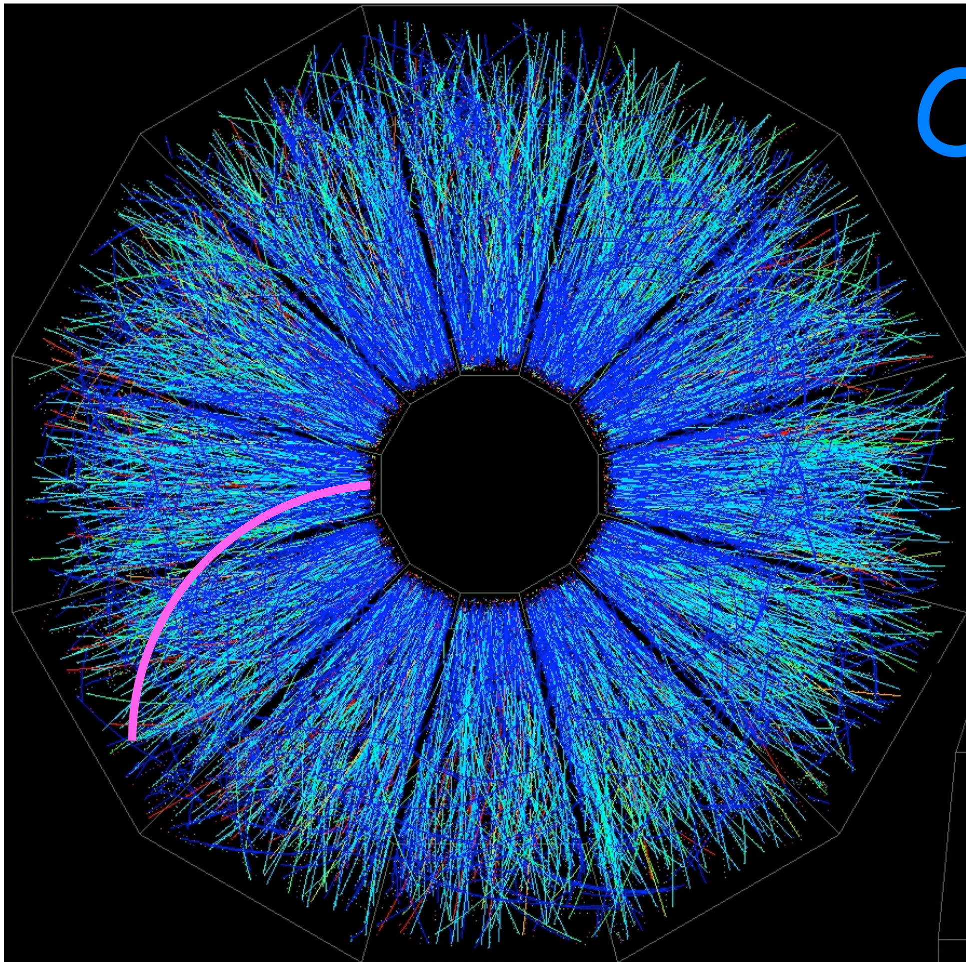
goal: track “all” charged hadrons (bags of quarks)
emitted in each collision



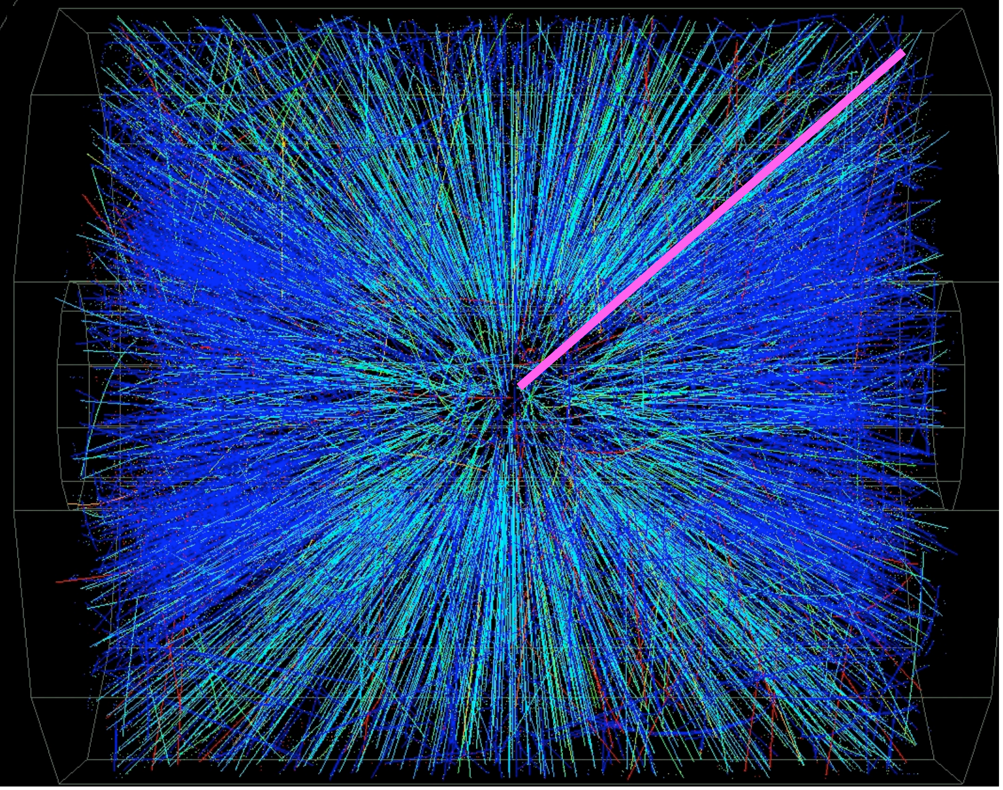
Operation of a Time Projection Chamber



One collision seen by STAR TPC



Momentum determined by track curvature in magnetic field…



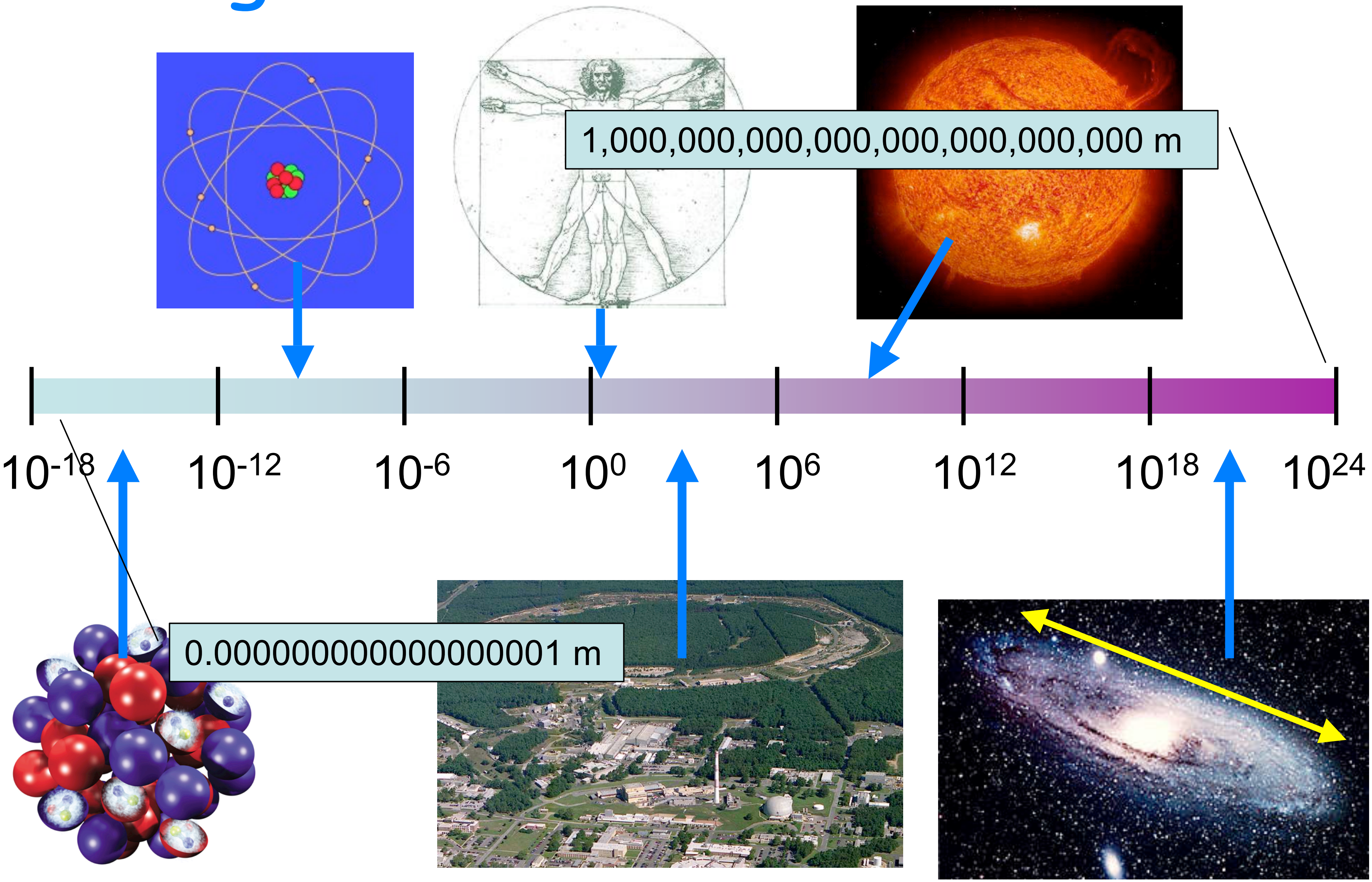
…and by direction relative to beam

“RHIC is big”

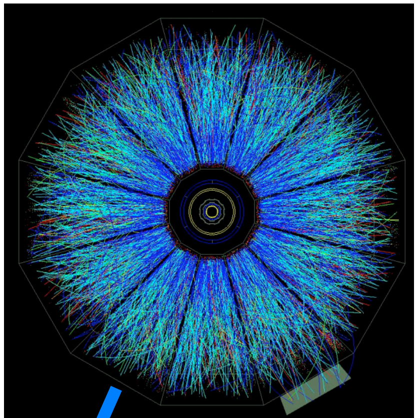
- big facility
- big detectors
- big collaborations
- “big” collisions

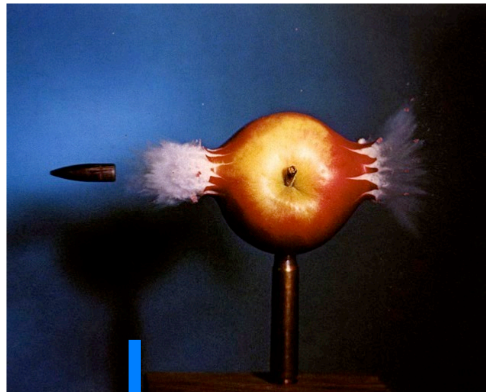
as seen by the Landsat-4 satellite…

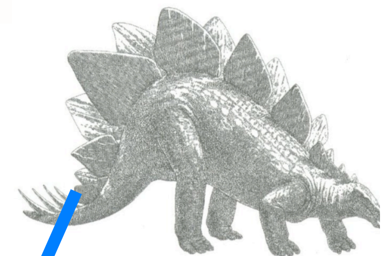
"Big" and "Small" - in meters

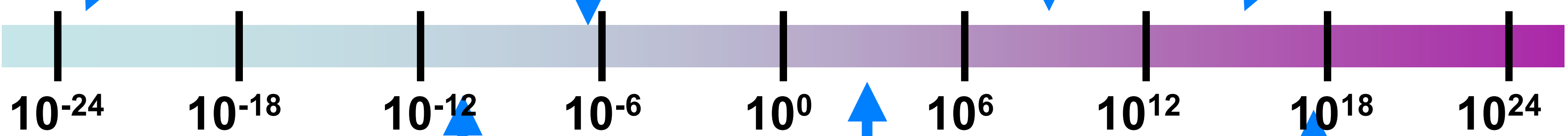


"Short" and "long" - in seconds

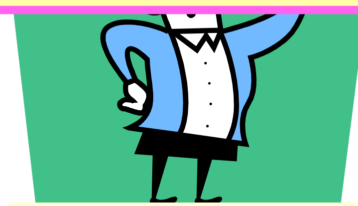




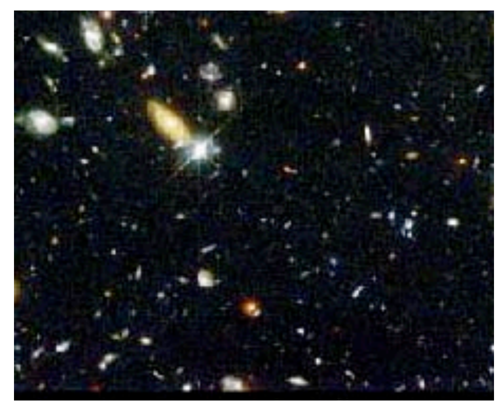




as many **yocto**seconds (10^{-24} s ~ 3 fm/c) in a second
as seconds in 10 thousand trillion years

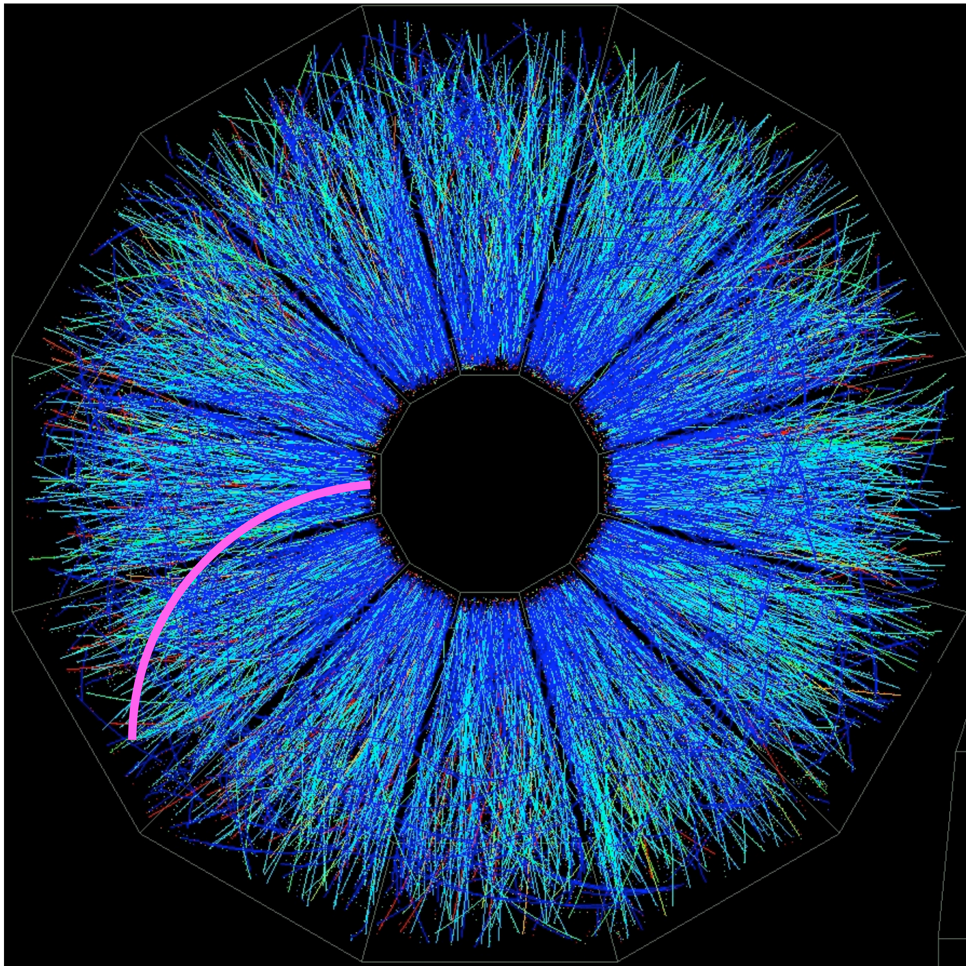


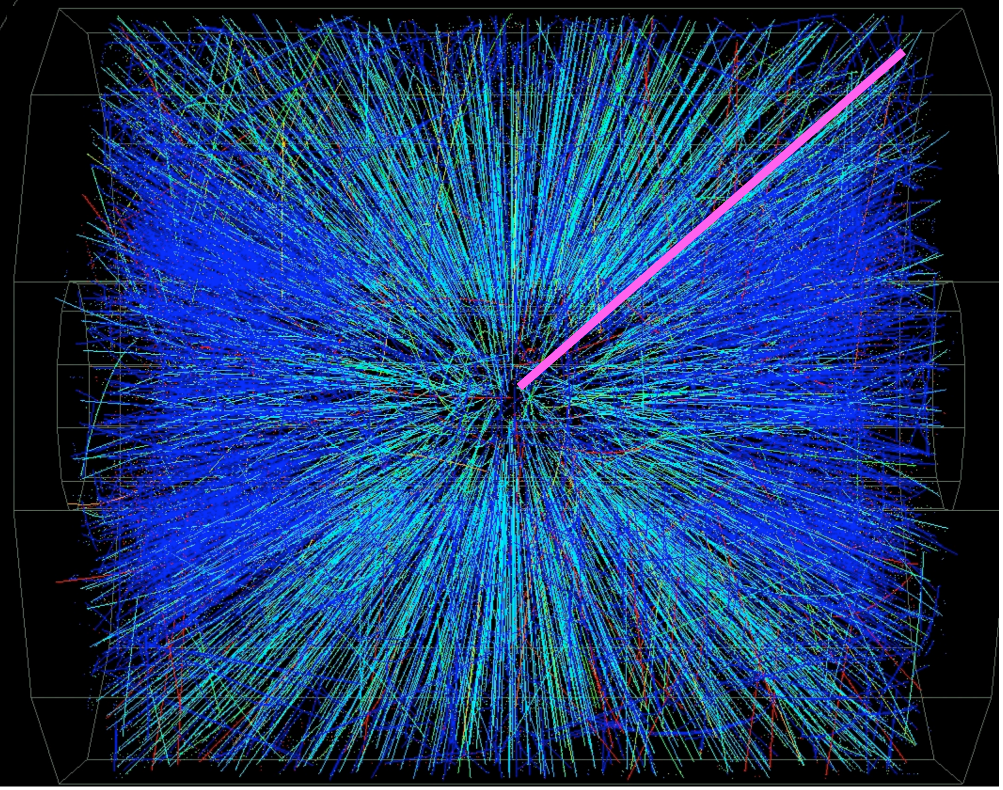
Today's lecture



Particle momentum from tracking…

… how to get particle *space-time* information??





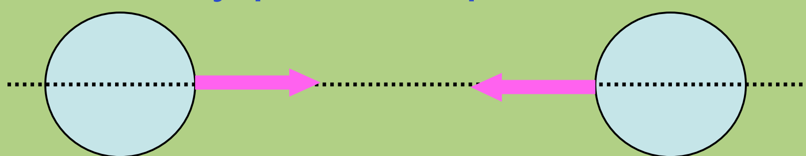
Impact parameter & Reaction plane

Impact parameter vector $\vec{b}$:

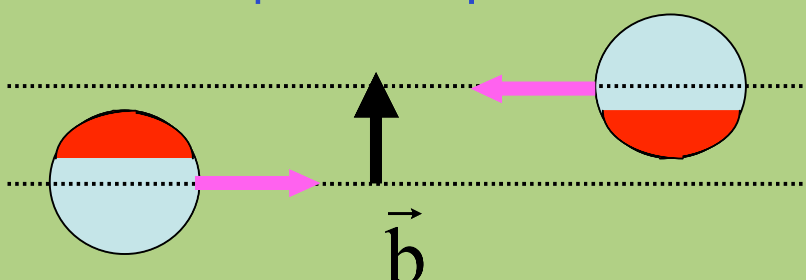
$\perp$ beam direction

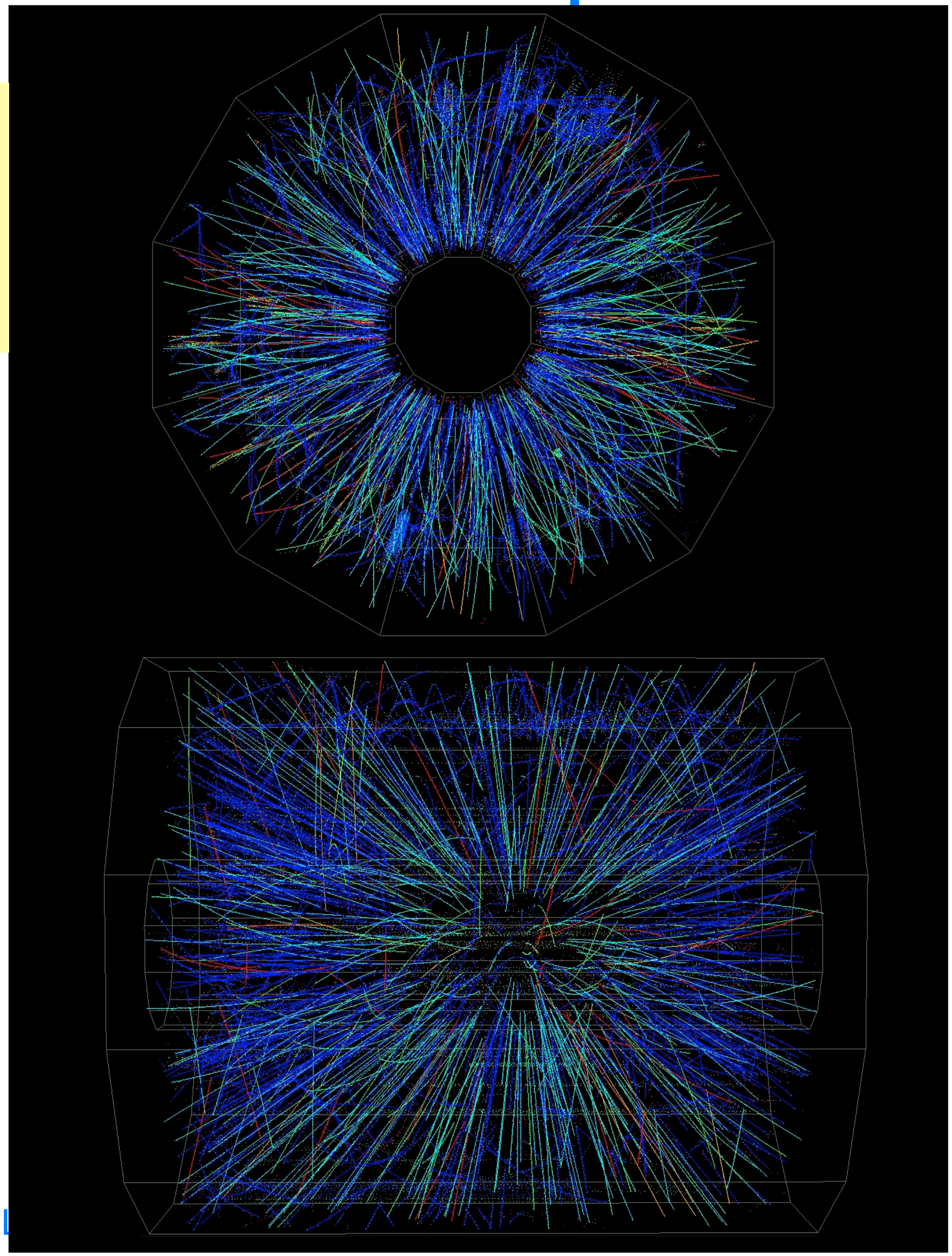
connects centers of colliding nuclei

b = 0 ⇔ "central collision"
many particles produced



"peripheral collision"
fewer particles produced





Impact parameter & Reaction plane

Impact parameter vector $\vec{b}$:

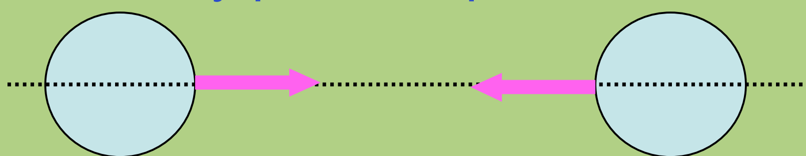
$\perp$ beam direction

connects centers of colliding nuclei

Reaction plane:

spanned by beam direction and $\vec{b}$

b = 0 ⇔ "central collision"
many particles produced



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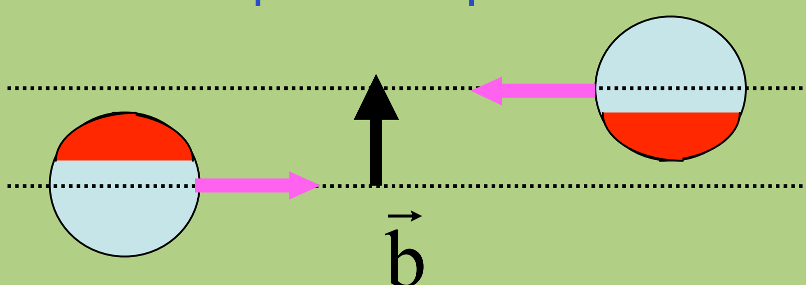
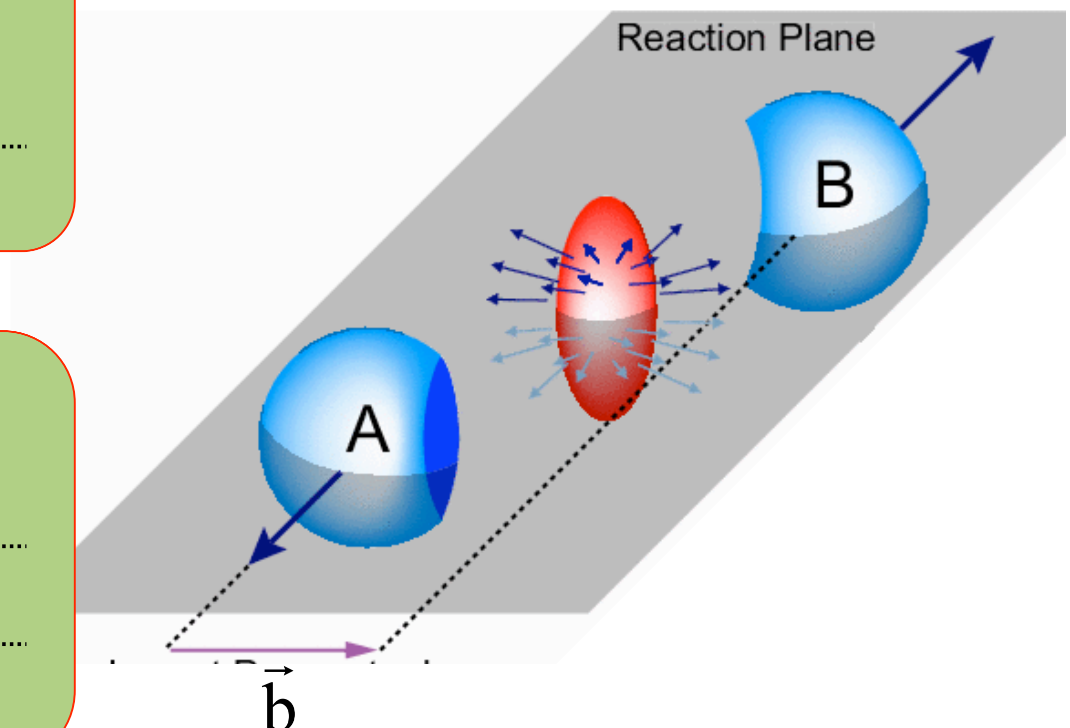
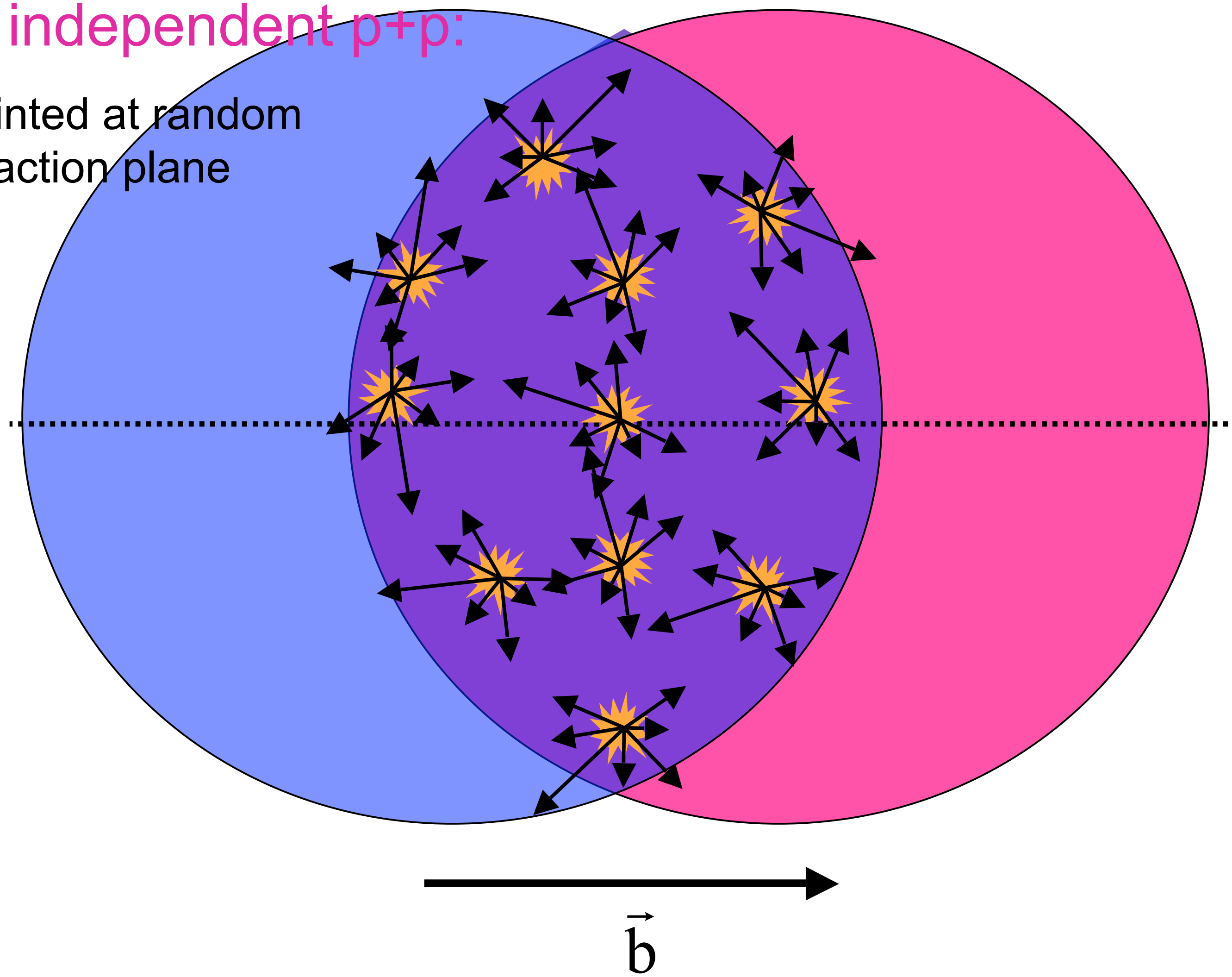




How do semi-central collisions evolve?

1) Superposition of independent p+p:

momenta pointed at random
relative to reaction plane



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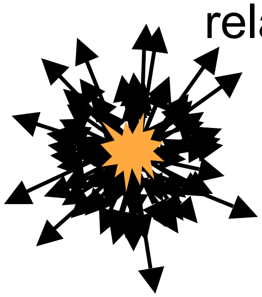
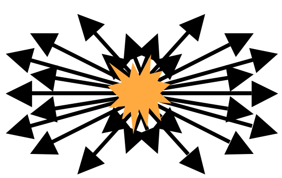


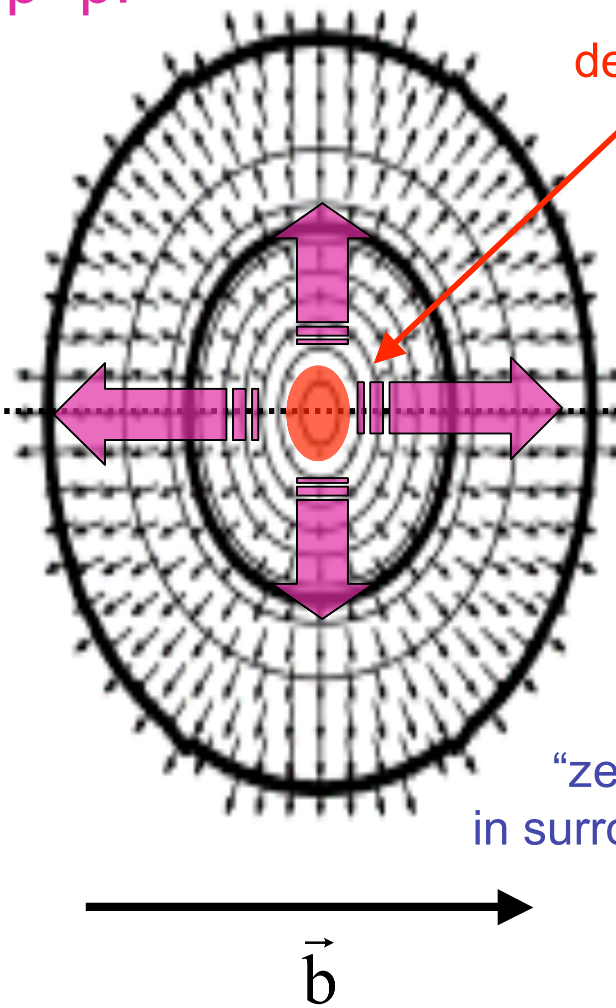
2) Evolution as a **bulk <u>system</u>**

Pressure gradients (larger in-plane)
push bulk "out" → "flow"



more, faster particles
seen in-plane

high
density / pressure
at center

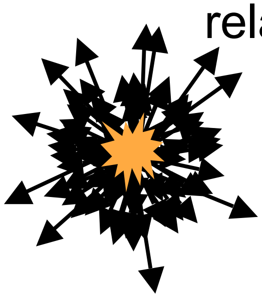


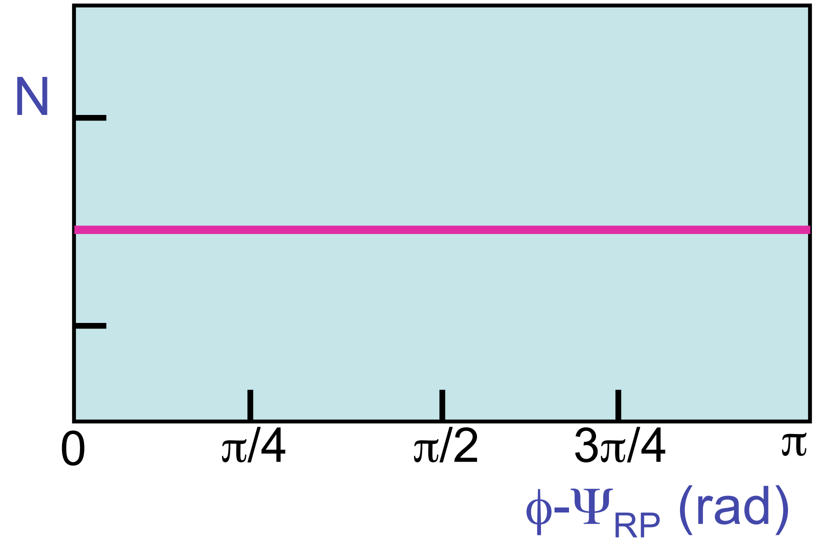
"zero" pressure
in surrounding vacuum

How do semi-central collisions evolve?

1) Superposition of independent p+p:

momenta pointed at random
relative to reaction plane





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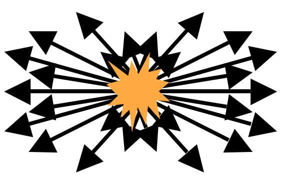

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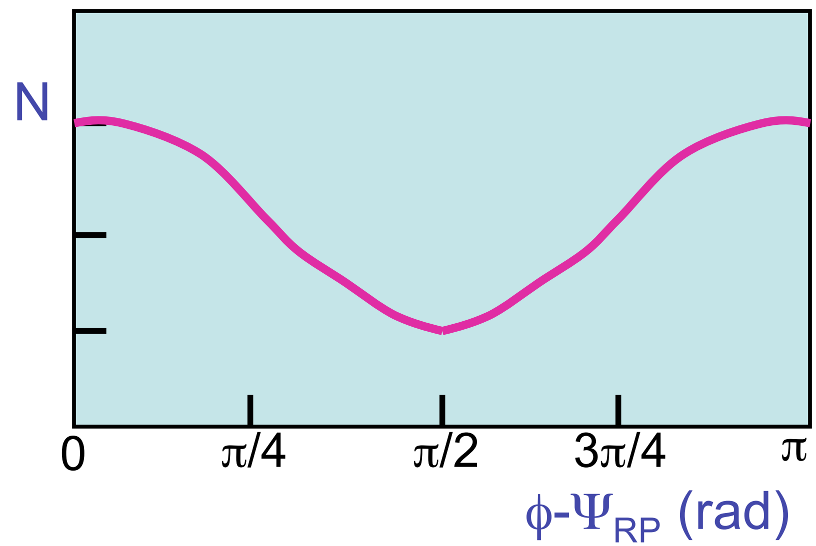
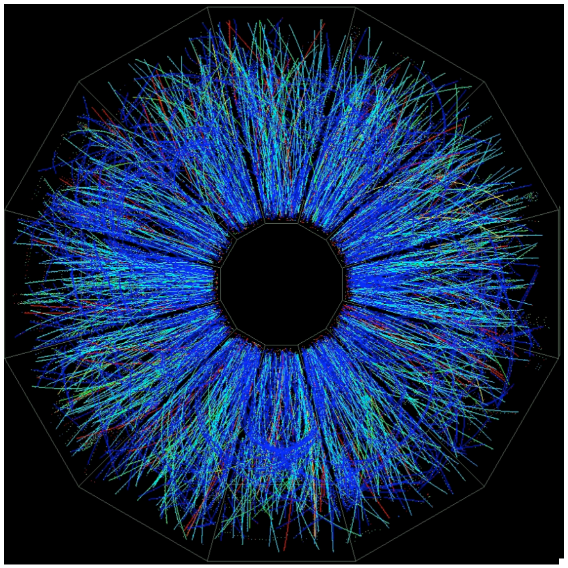
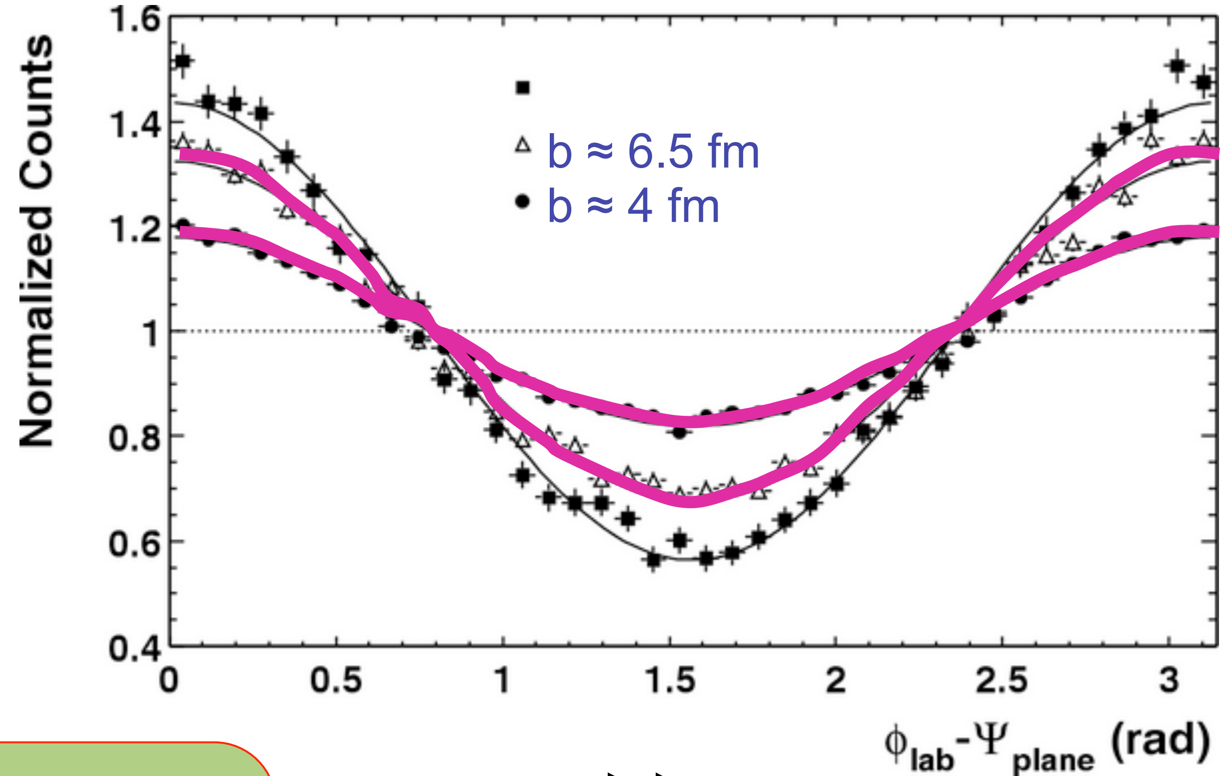


Azimuthal distributions at RHIC

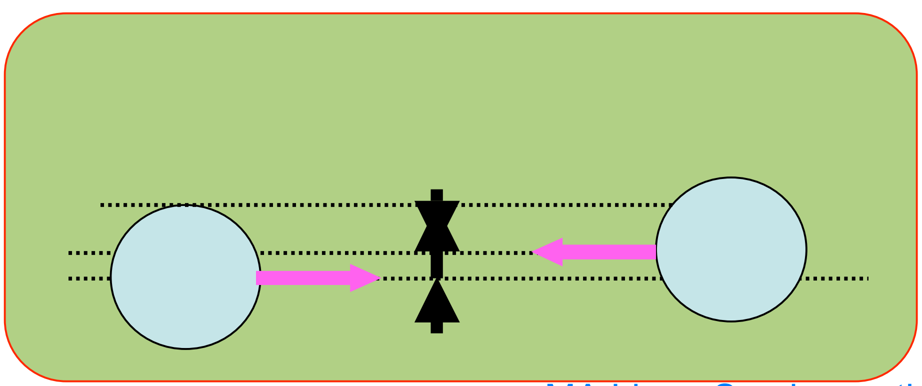


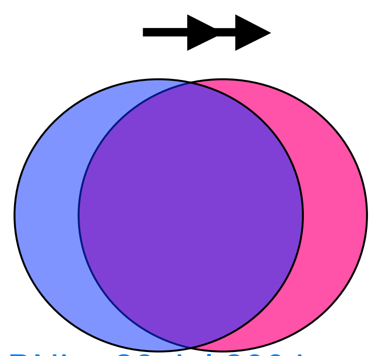
STAR, PRL**90** 032301 (2003)



mid-central collisions

“central” collisions





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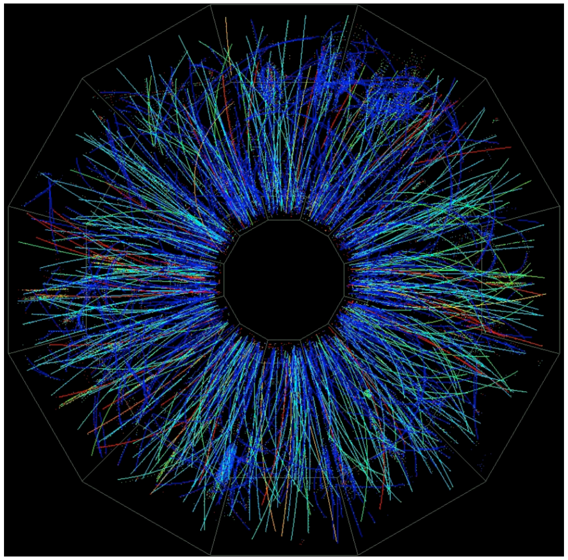

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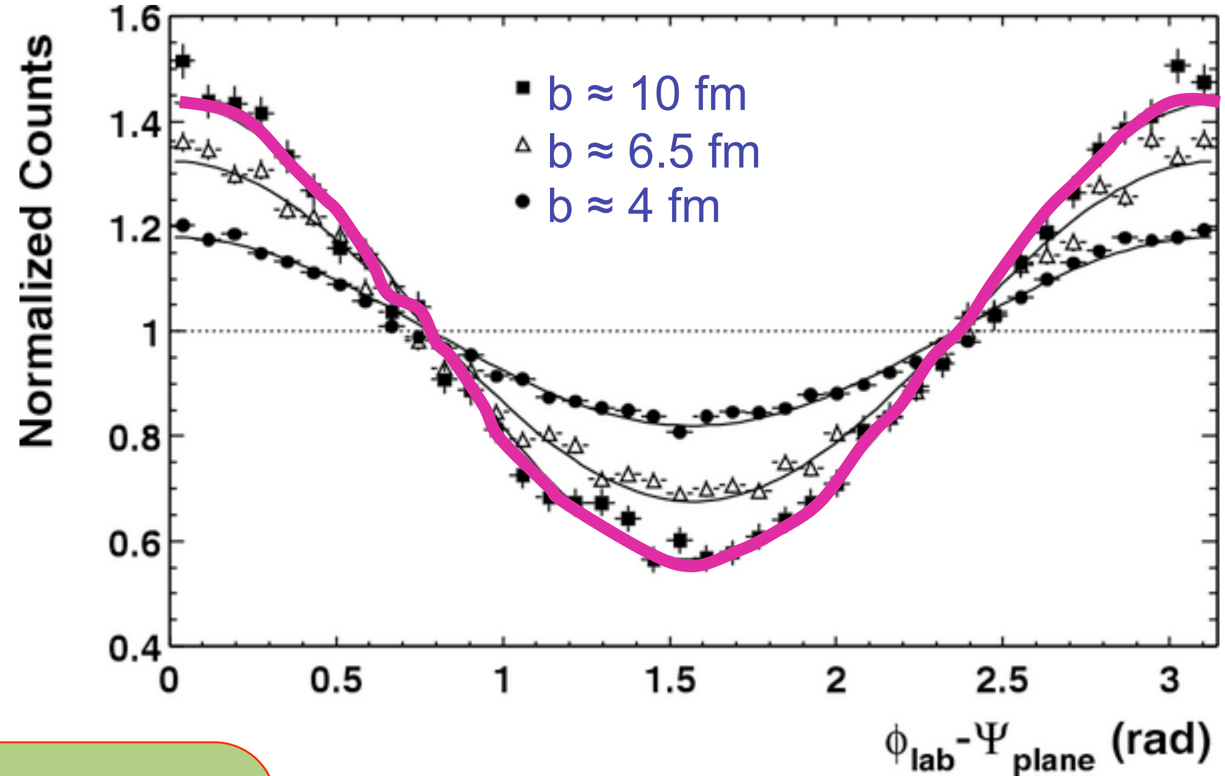
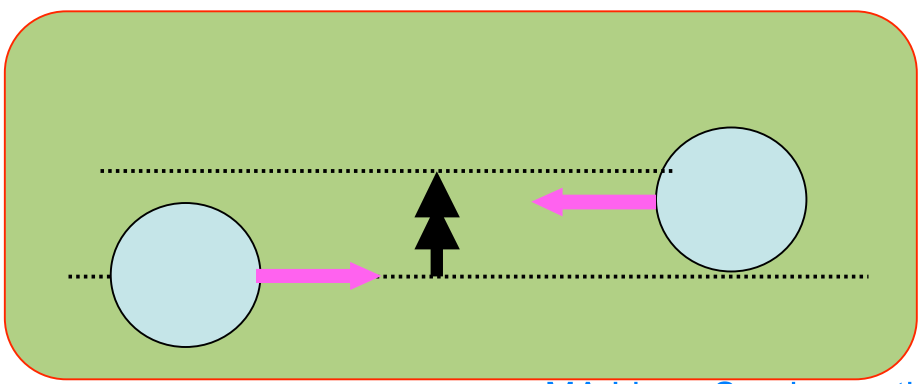
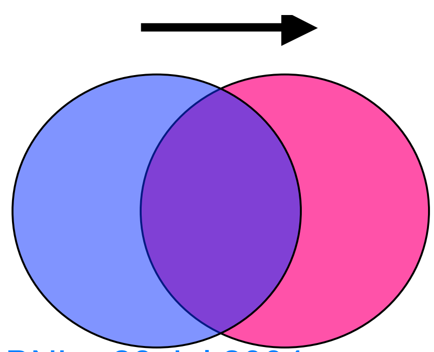


peripheral collisions

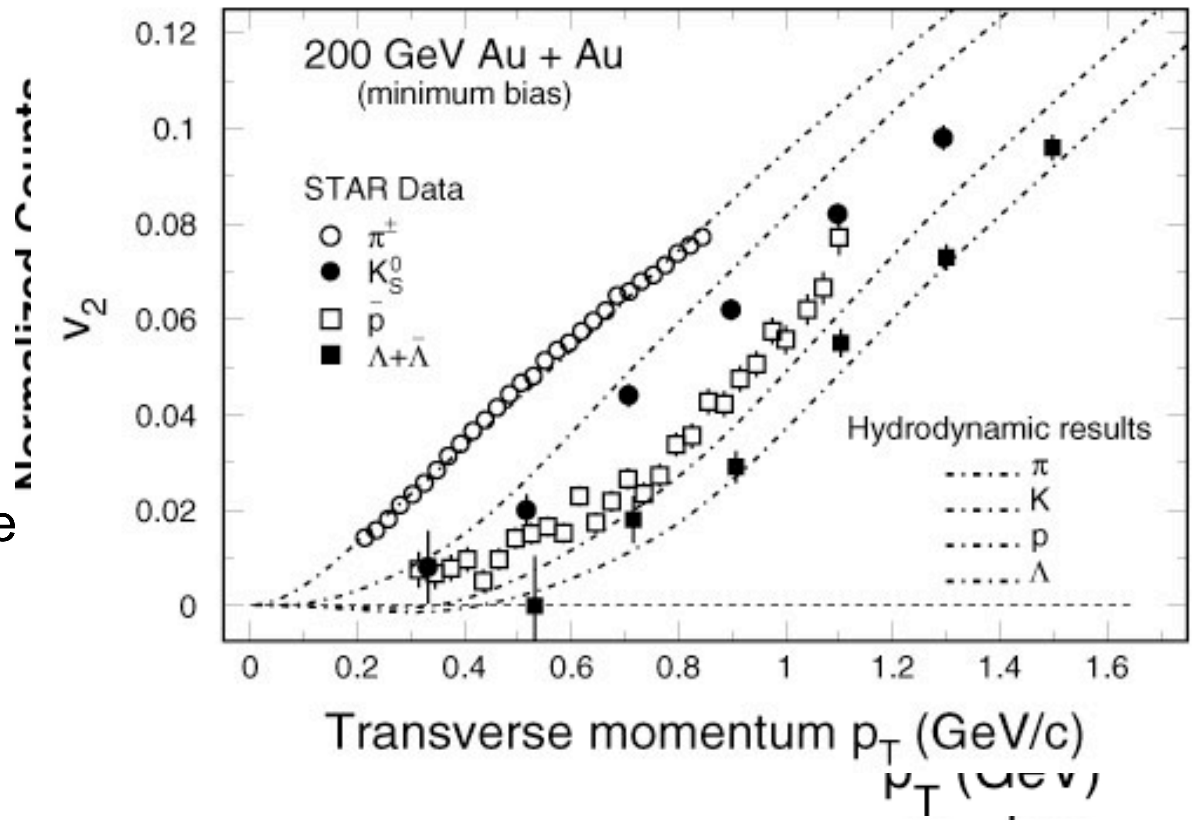




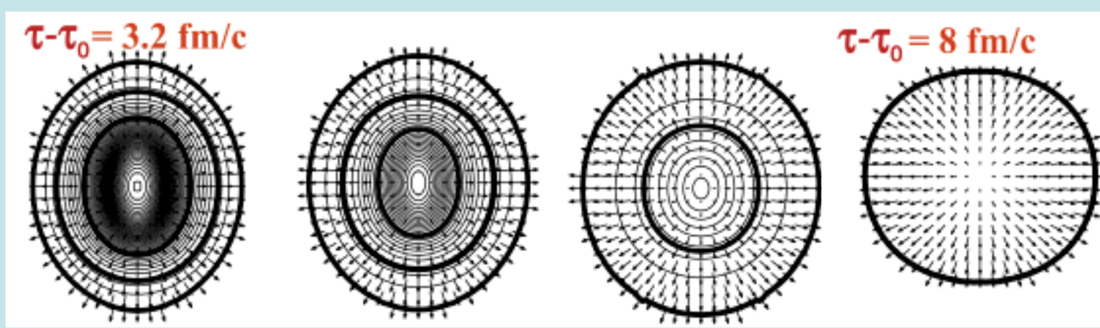
Elliptic flow – collectivity & sensitivity to *early* system

"Elliptic flow"

- evidence of *collective* motion
- quantified by v_2
- geometrical anisotropy → momentum anisotropy
- sensitive to *early* pressure
- evidence for
  - early thermalization
  - QGP in early stage



Hydrodynamic calculation of ***system*** *evolution*



A more direct handle?

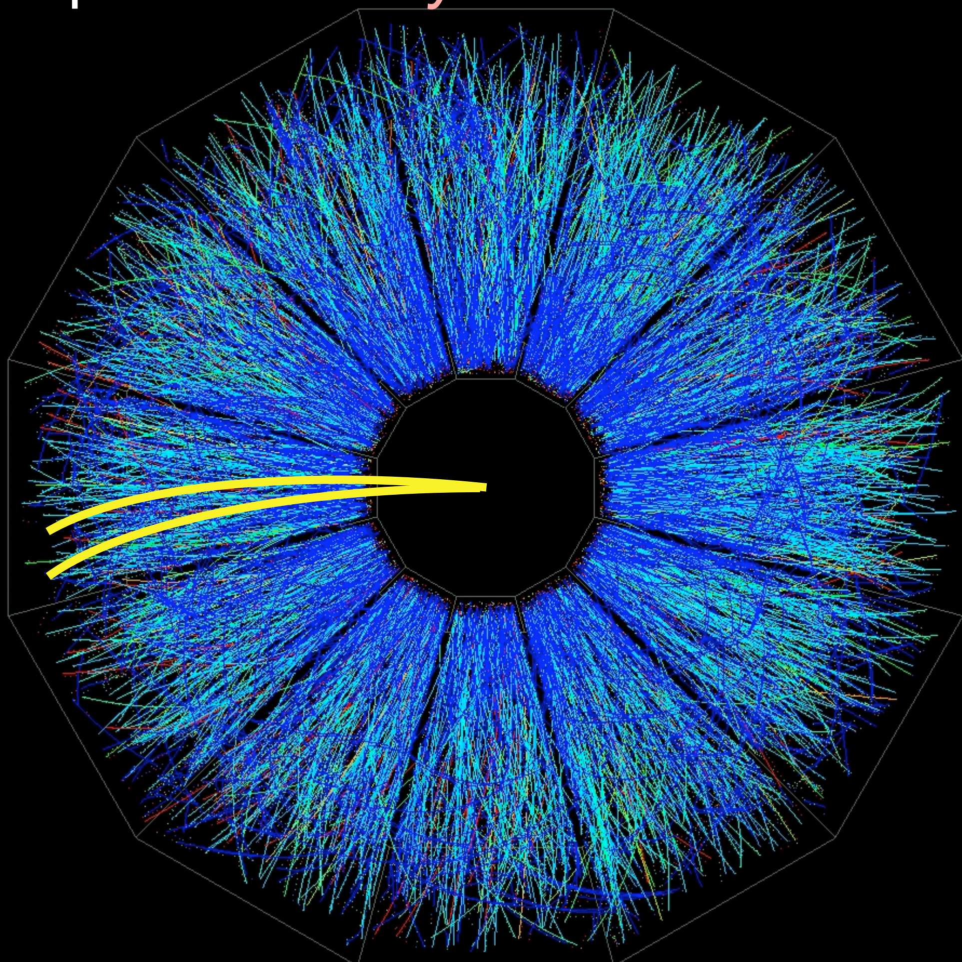
- elliptic flow (v_2) and other measurements (not discussed) → evidence towards QGP at RHIC
  - indirect connection to geometry

- Are there more direct handles on the space-time geometry of collisions?
  - yes ! Even at the 10^{-15} m / 10^{-23} s scale !
- What can they tell us about the QGP and system evolution?

Warning: some quantum mechanics coming
(feel free to concentrate on "bottom line")

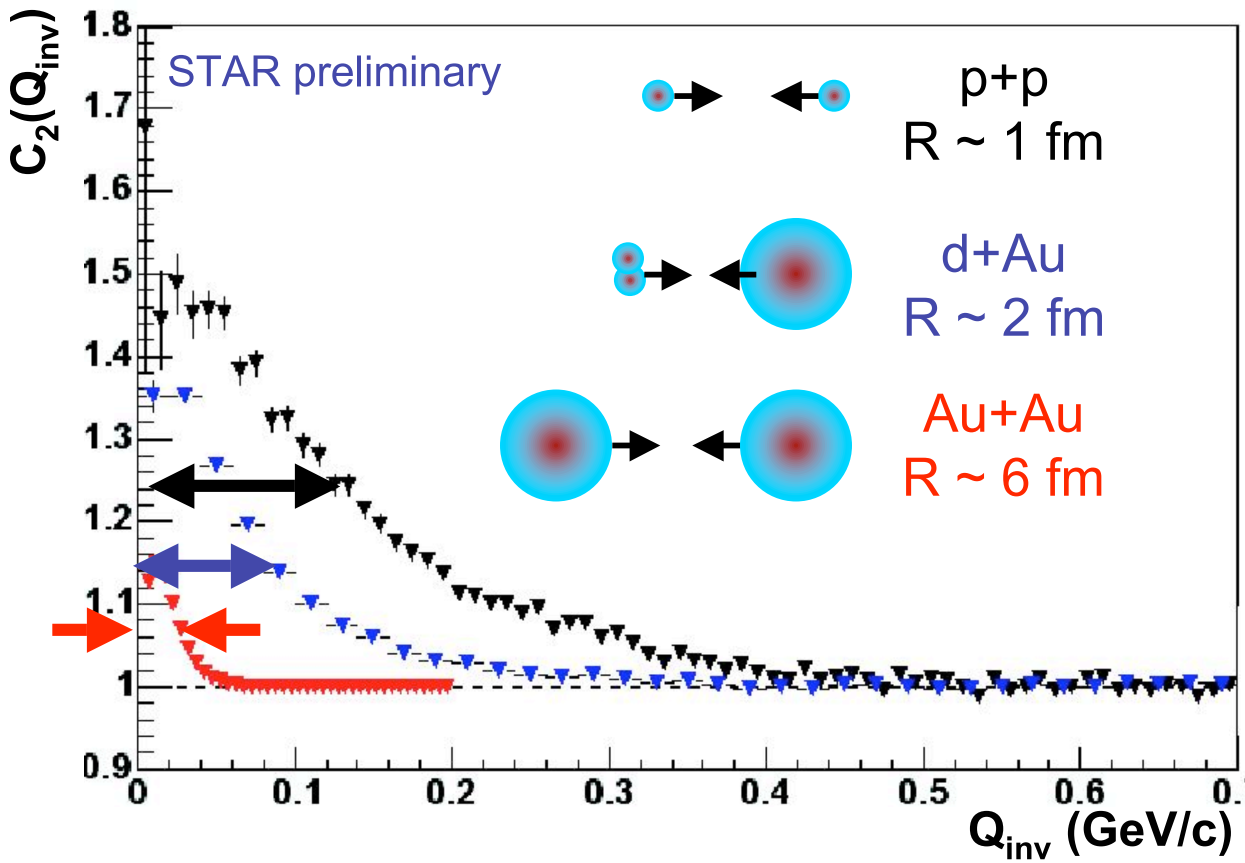
The Bottom line…

if a pion is emitted, it is more likely to emit another pion *with very similar momentum* if the source is small



experimentally measuring this enhanced probability: quite challenging

Correlation functions for different colliding systems



Different colliding systems studied at RHIC

Interferometry probes the smallest scales ever measured !

More detailed geometry

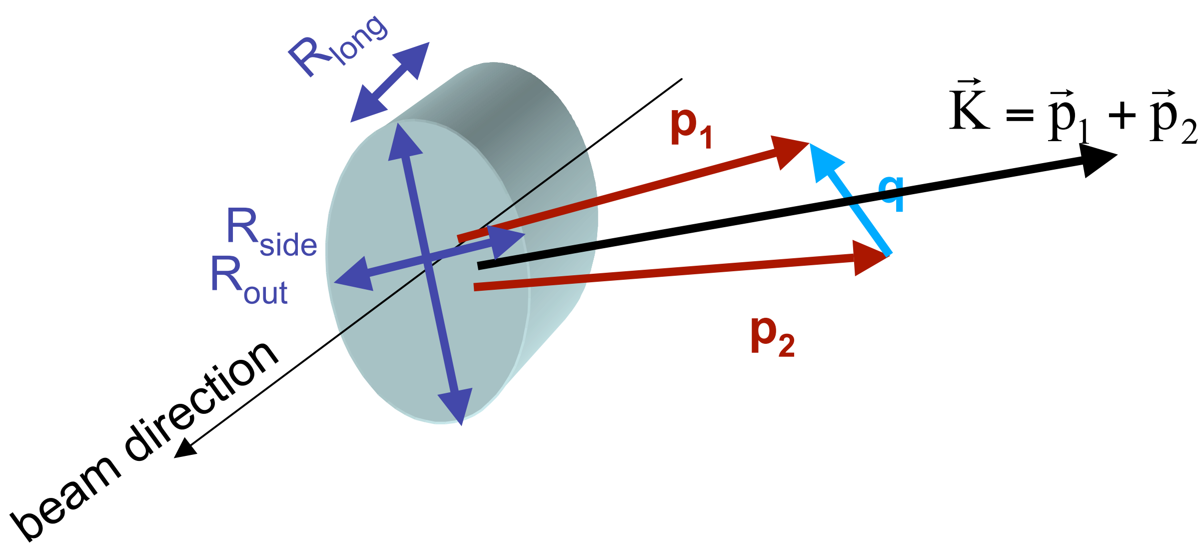
Relative momentum between pions is a **vector** $\vec{q} = \vec{p}_1 - \vec{p}_2$

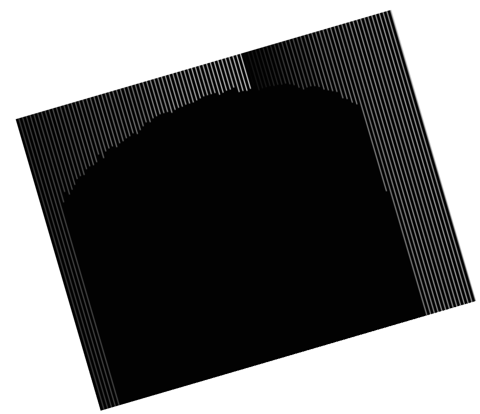
→ can extract 3D shape information

R_{long} – along beam direction

R_{out} – along “line of sight”

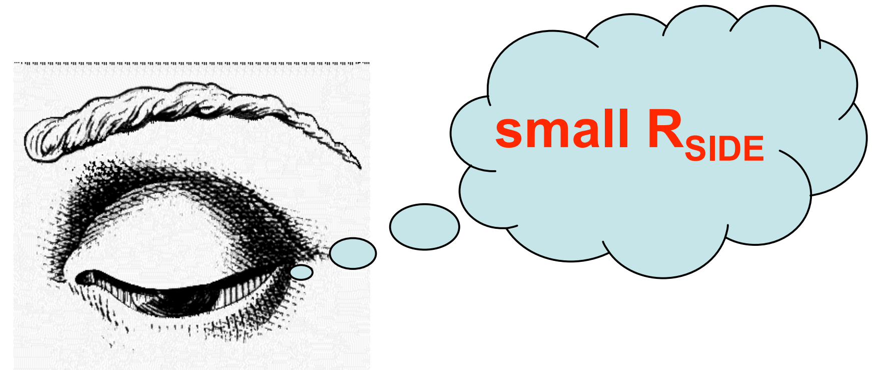
R_{side} – ⊥ “line of sight”

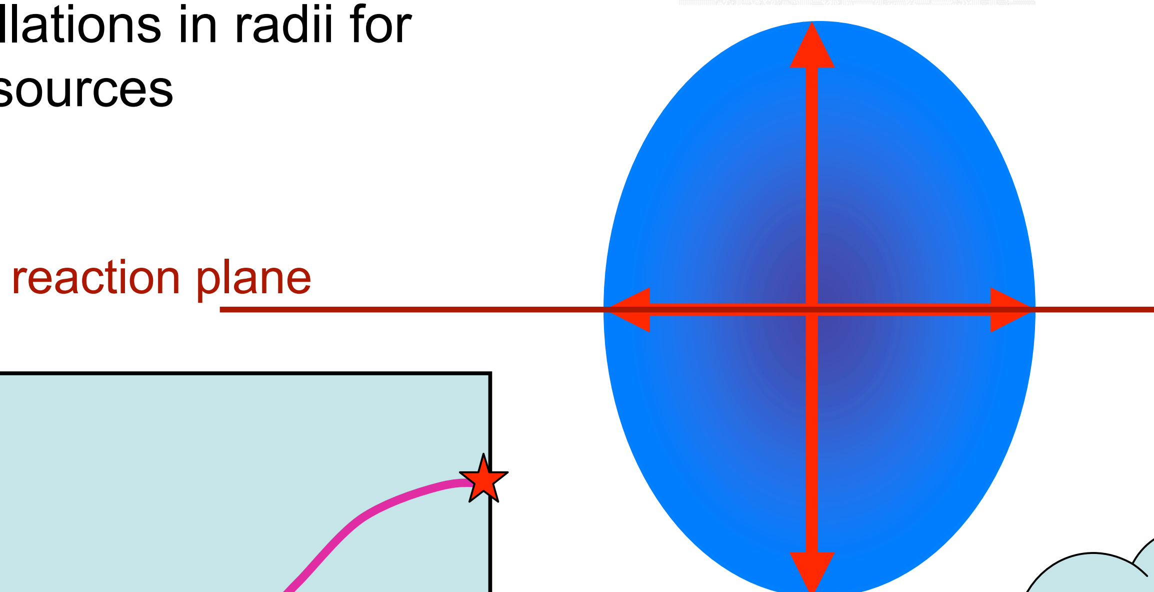


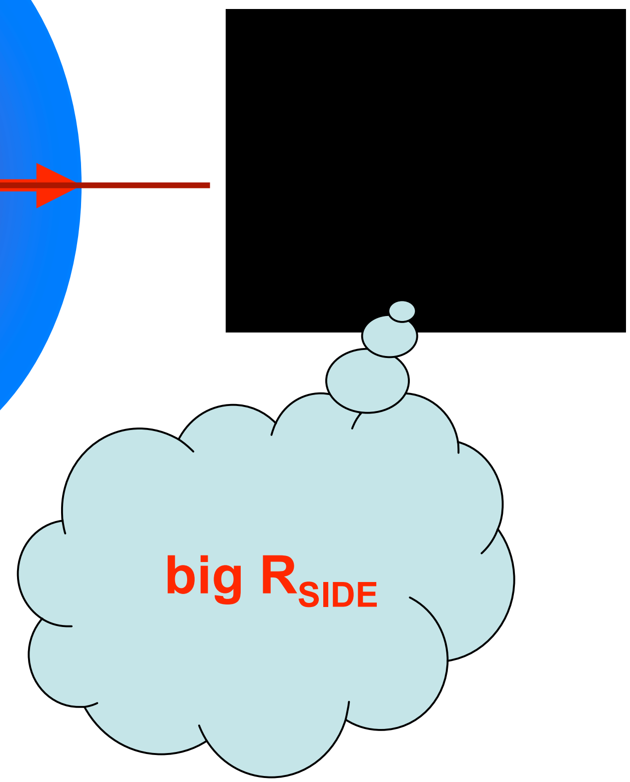


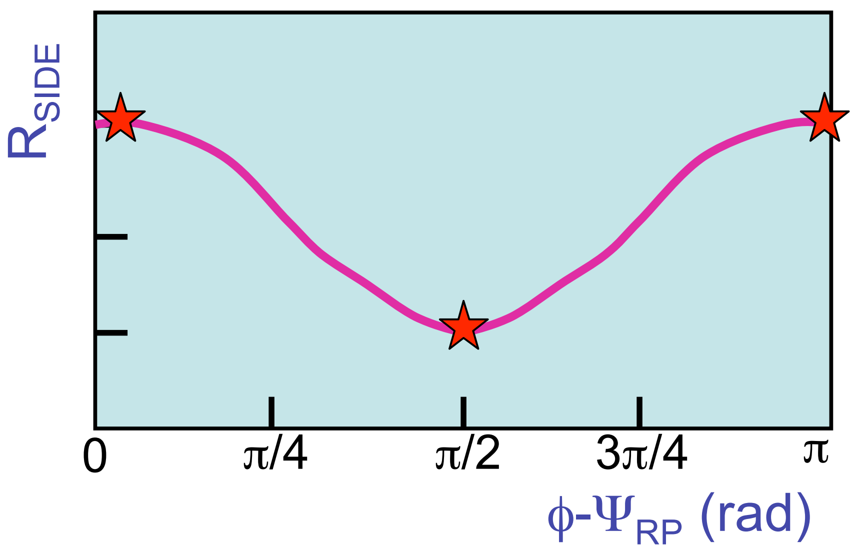
Source shape

- "observe" the source from all angles relative to the reaction plane
- expect oscillations in radii for non-round sources









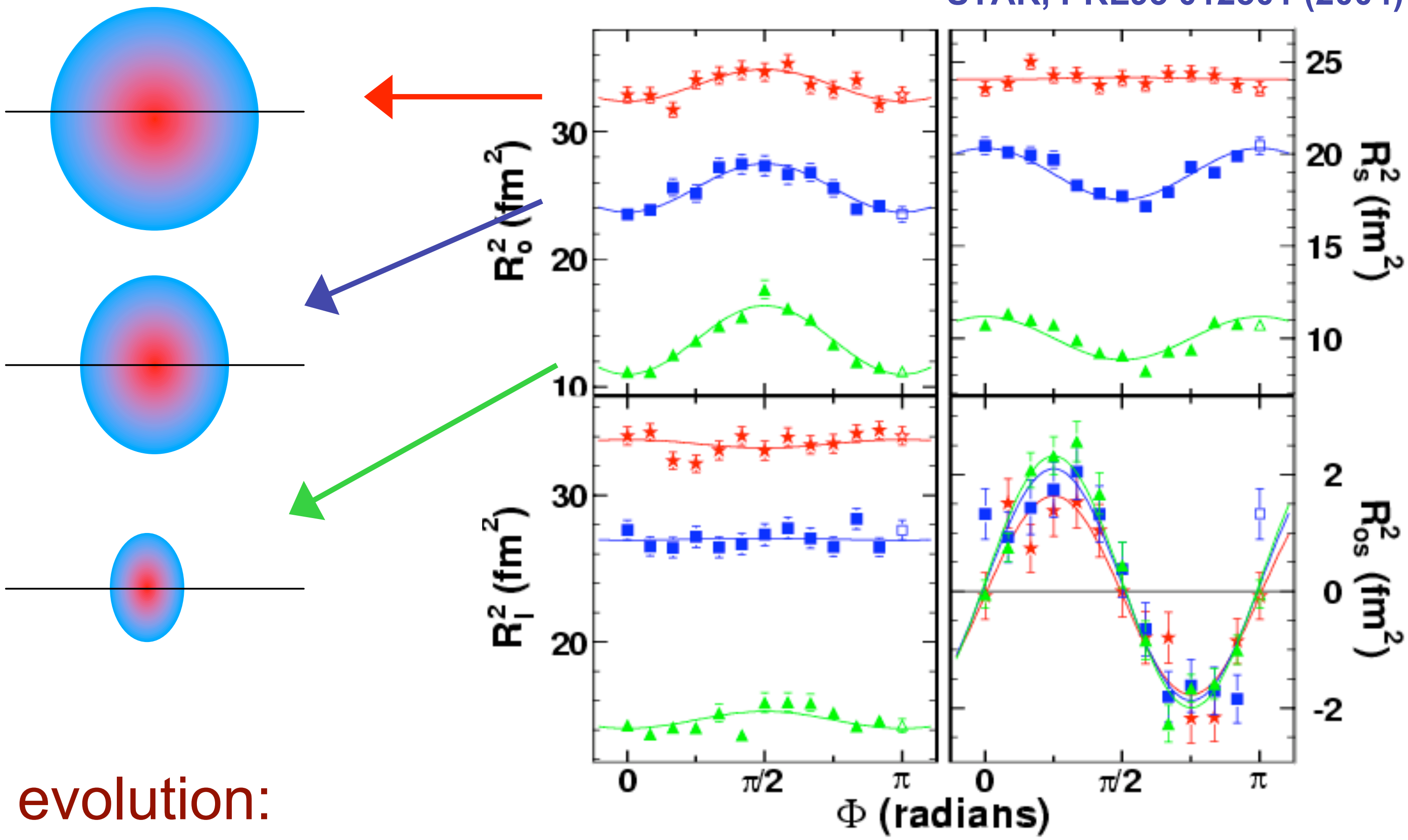
Measured *final* source shape

STAR, PRL93 012301 (2004)

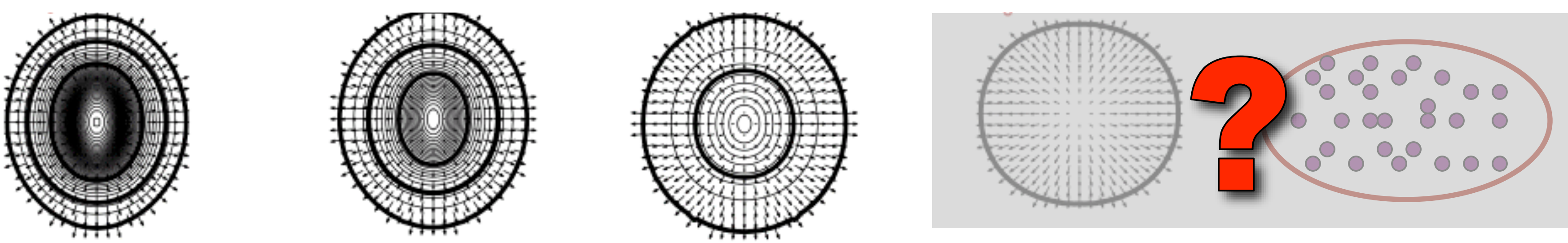
central collisions

mid-central collisions

peripheral collisions



Expected evolution:

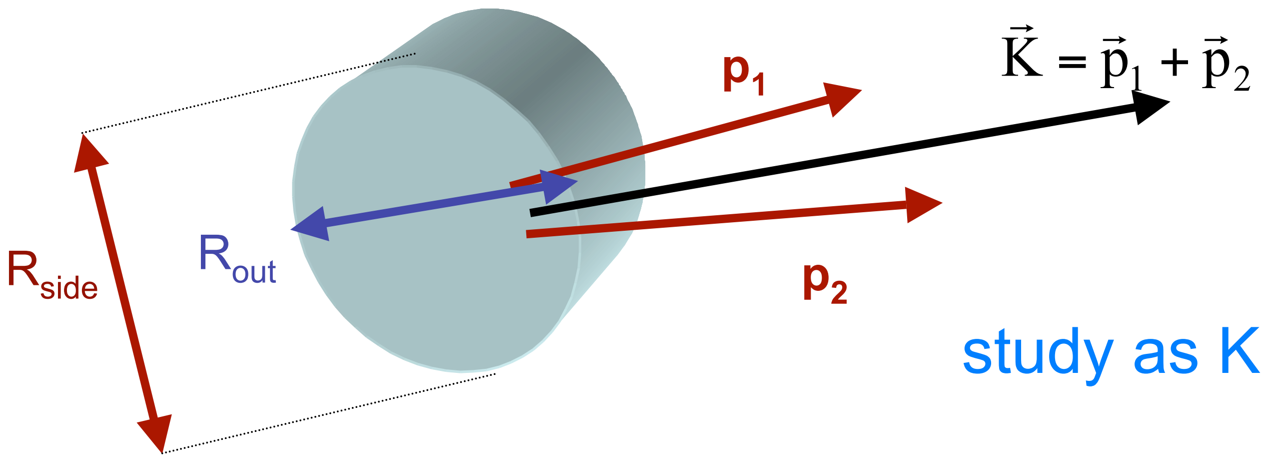


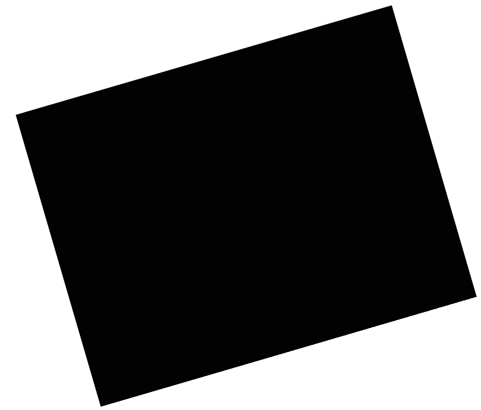
More information

Relative momentum between pions is a **vector** $\vec{q} = \vec{p}_1 - \vec{p}_2$

→ can extract 3D shape information

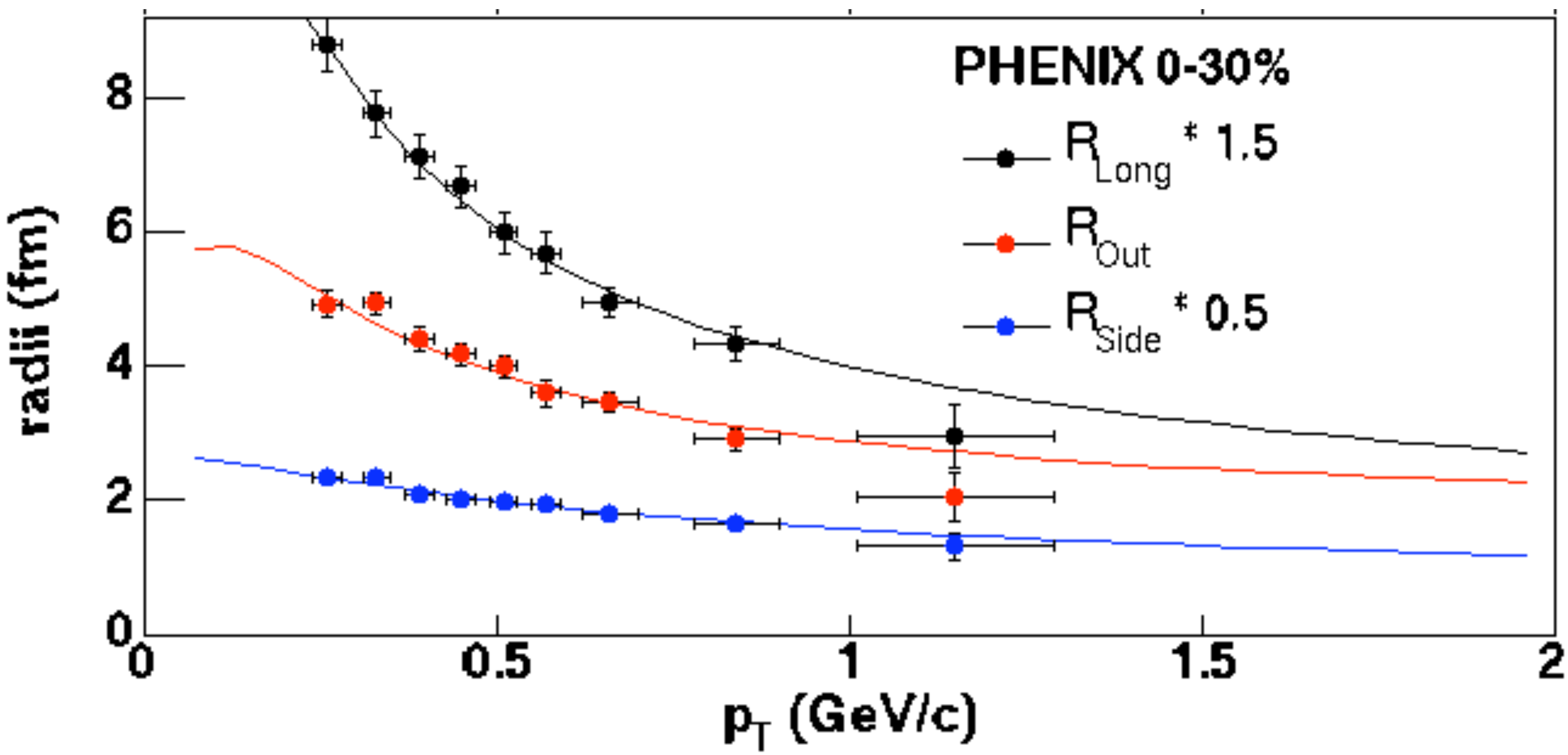
- R_{long} – along beam direction
- R_{out} – along "line of sight"
- R_{side} – ⊥ "line of sight"





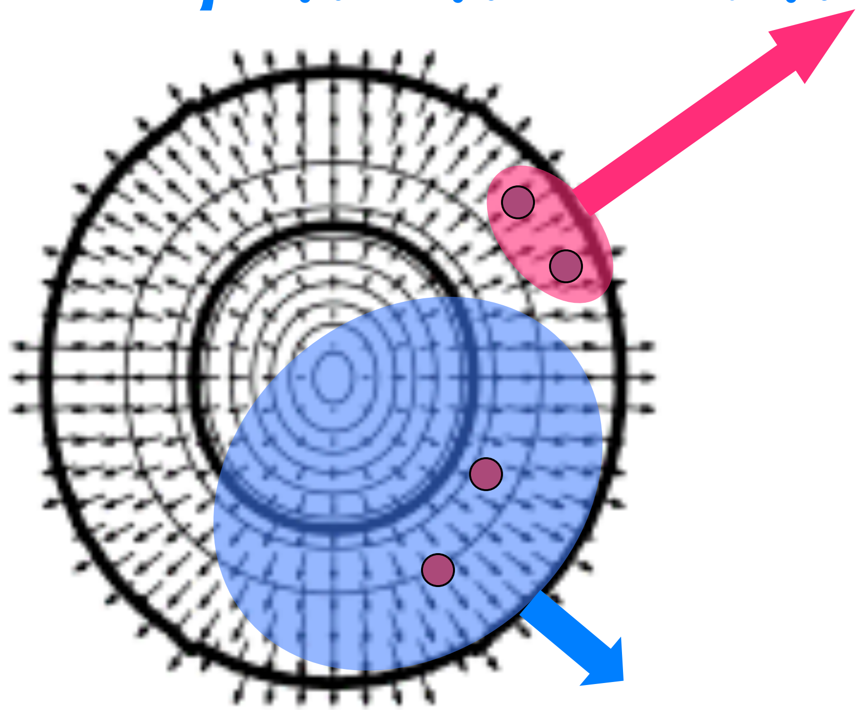
study as K grows…

Why do the radii fall with increasing momentum ??



Why do the radii fall with increasing momentum [redacted]

It's collective flow !!



Direct geometrical/dynamical evidence
for bulk behaviour!!!

Amount of flow consistent with p-space

Timescales

- Evolution of source shape
  - suggests system lifetime is shorter than otherwise-successful theory predicts

- Is there a more direct handle on timescales?

Disintegration timescale

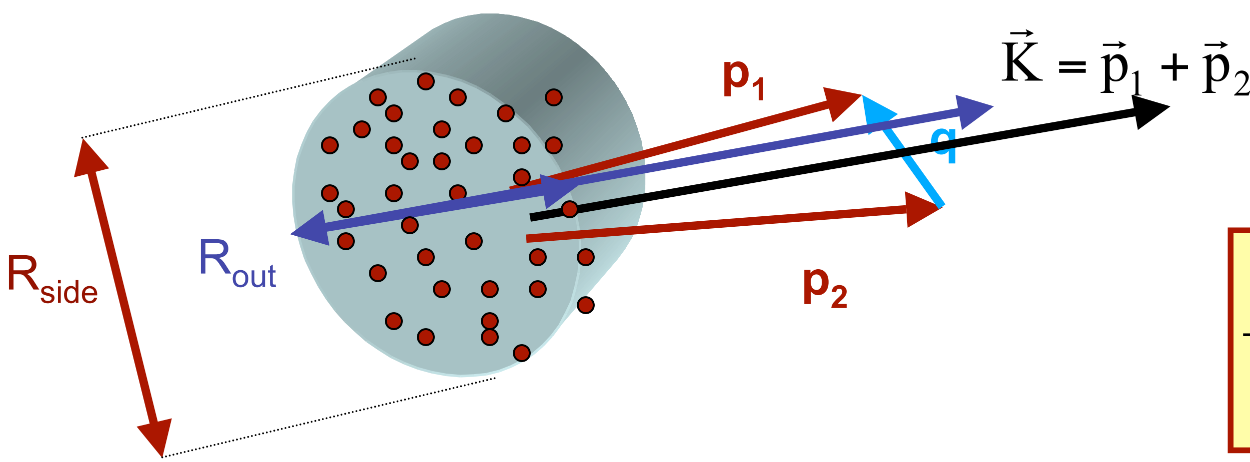
Relative momentum between pions is a **vector** $\vec{q} = \vec{p}_1 - \vec{p}_2$

→ can extract 3D shape information

R_{long} – along beam direction

R_{out} – along "line of sight" ← increases with emission timescale

R_{side} – ⊥ "line of sight"

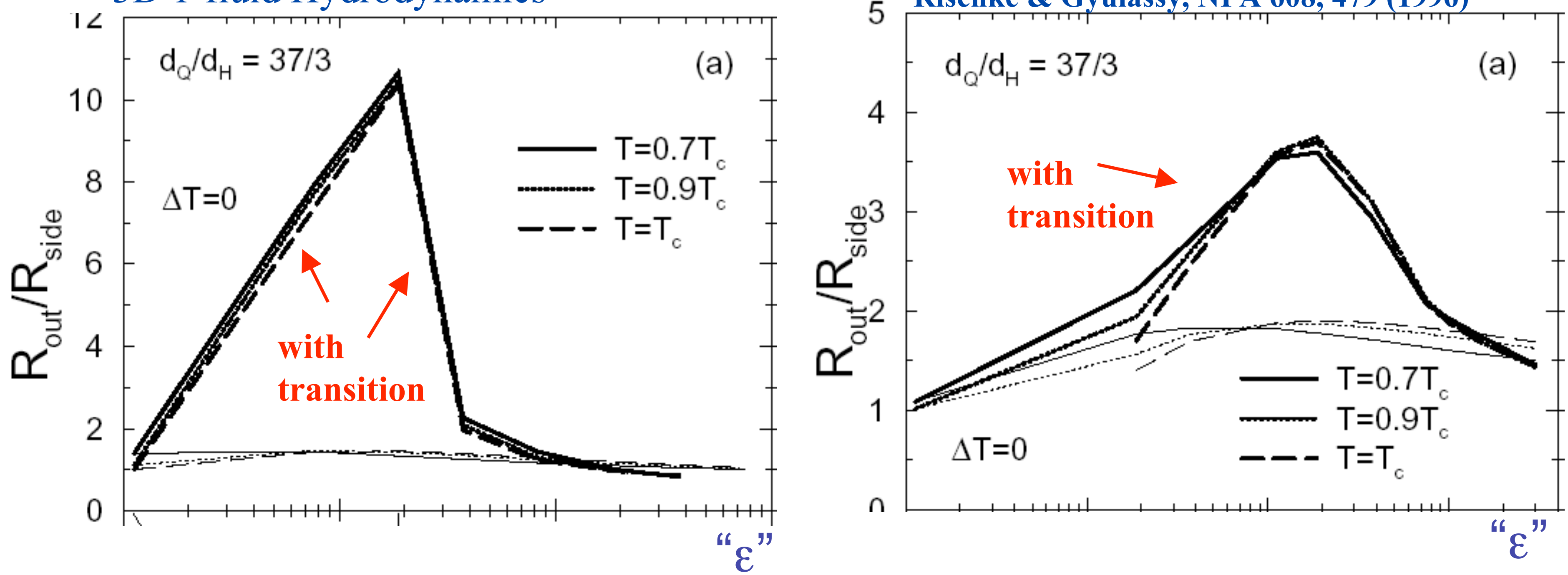


$$\boxed{\frac{R_{OUT}}{R_{SIDE}} \leftrightarrow \tau}$$

Disintegration timescale - expectation

3D 1-fluid Hydrodynamics

Rischke & Gyulassy, NPA 608, 479 (1996)

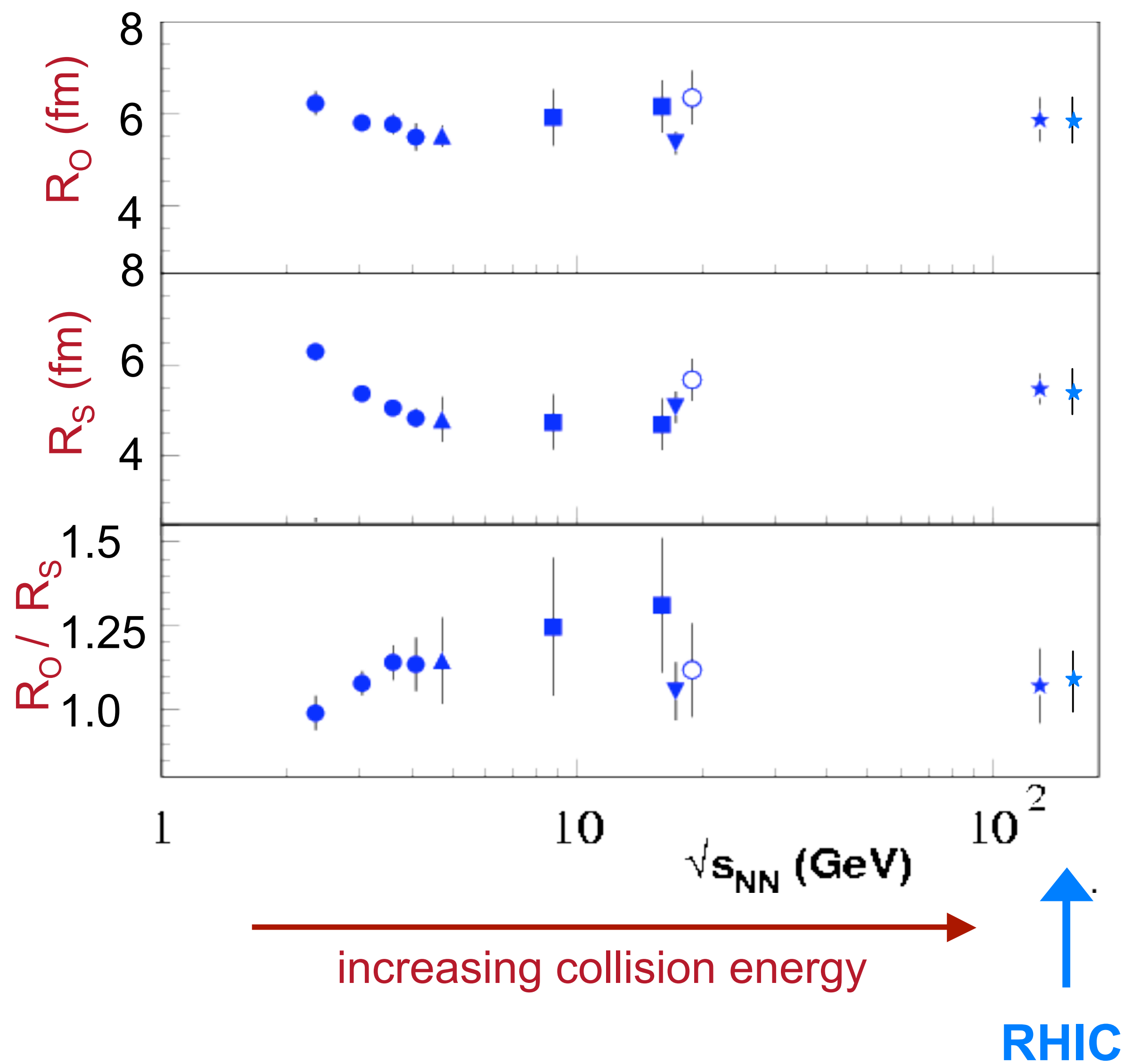


Long-standing favorite signature of QGP:

- increase in τ, R_{OUT}/R_{SIDE} due to deconfinement ↔ confinement transition
- expected to "turn on" as QGP energy threshold is reached

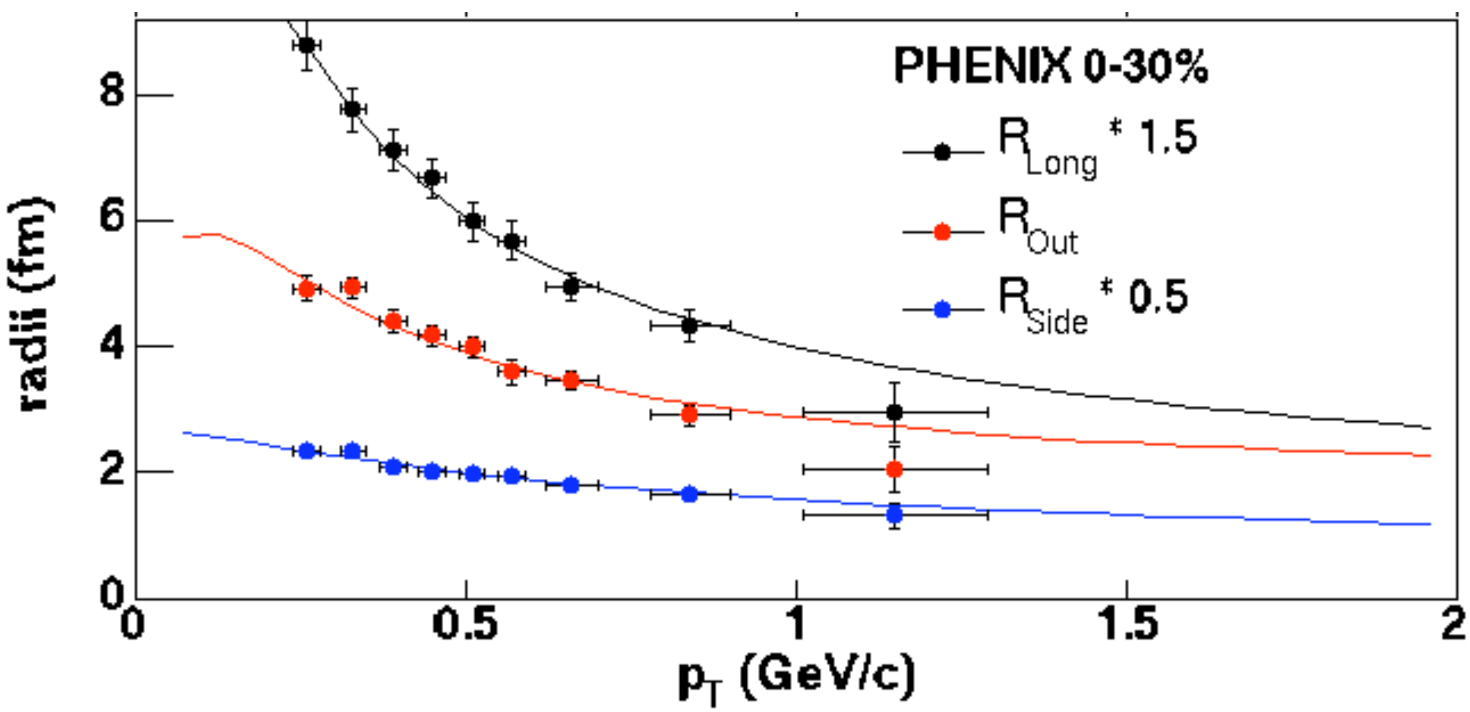
Disintegration timescale - observation

- no threshold effect seen
- $R_O/R_S \sim 1$



Disintegration timescale - observation

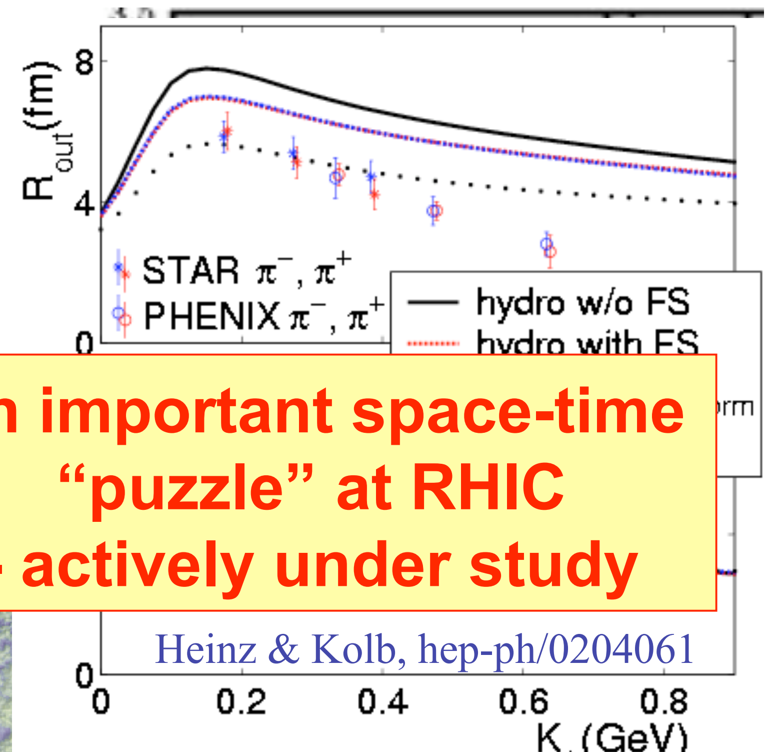
- no threshold effect seen
- $R_O/R_S \sim 1$
- toy model calculations
  suggest very short timescales

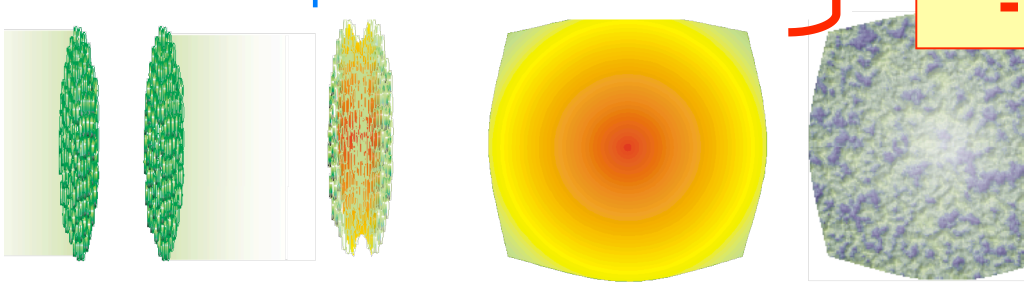


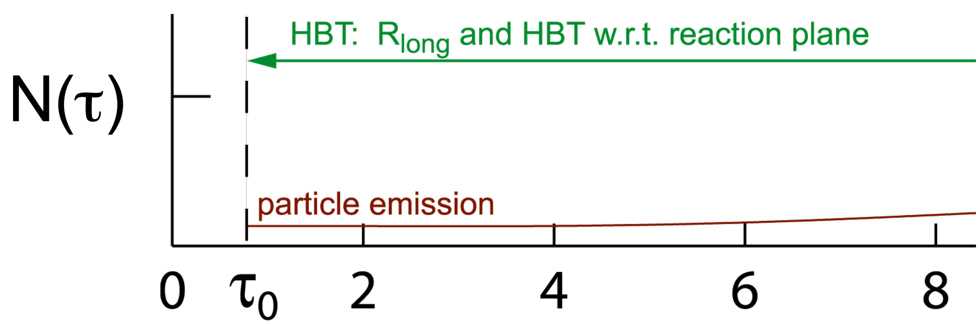
Disintegration timescale - observation

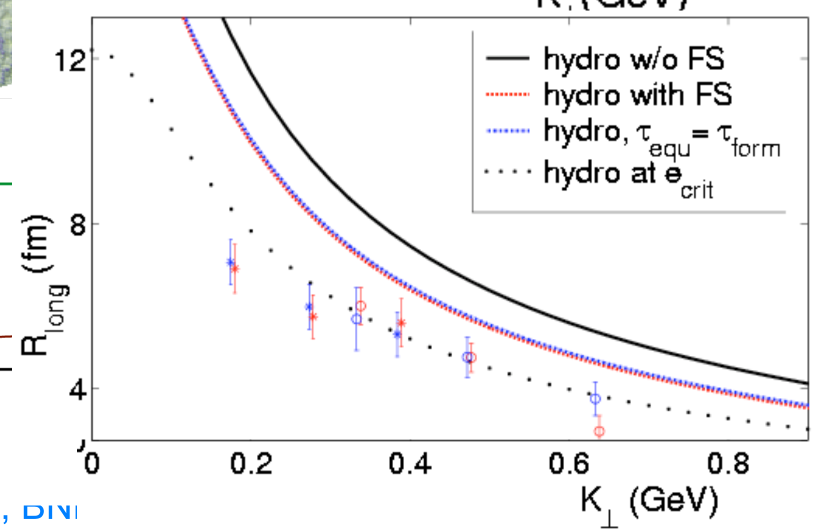
- no threshold effect seen
- $R_O/R_S \sim 1$
- toy model calculations
  suggest very short timescales
  - rapid, explosive evolution
  - *too* explosive for "real" models
    which explain all *other* data

An important space-time "puzzle" at RHIC - actively under study









Summary

- Crucial feature of strong force: confinement
  - study *bulk* system of *deconfined* quarks
- bulk system *is* created in heavy ion collisions at RHIC !
- geometric (v_2) and other measurements strongly suggest bulk *deconfined* matter !
- We *can* access the smallest size and time scales through quantum-mechanical mechanism of interferometry
  - close investigation of space-time: our understanding of the hot, dense system evolution is incomplete
- Focusing on holes in understanding-- key to scientific progress
  - these are exciting times in our study of the least well-understood force in Nature … and clearly size matters in this quest !